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IONOSPHERIC EQUIVALENT SLAB THICKNESS AND ITS
MODELING APPLICATIONS

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13. ABSTRACT (Maximum 200 words) A database of equivalent slab thickness observations covering nearly two complete solar cycles has been obtained at a mid-latitude site (Hamilton, MA). This database has been studied for correlations between the various parameters as well as for dependencies on observable quantities. The mean variations of T are described both qualitatively, in terms of changes to profile shapes, and quantitatively, in terms of a simple numerical model. A preliminary investigation of the day-to-day variations of T is also described. The similarity of the mean numerical T model to one obtained using data from a site in Wales (U.K.) suggests that longitude variations of T may well be small at mid-latitudes. This property has in turn been used to convert a network of ionosonde observations to a database of TEC, for comparisons with a number of currently available ionospheric models. These same ionospheric models were also used to predict values of T over Hamilton, MA, and the comparisons provided additional model validation. Adjustments to the model profiles were suggested in a couple of cases.				
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TABLE OF CONTENTS

1. INTRODUCTION	1
2. THE DATABASE	4
3. DESCRIBING THE VARIATIONS OF SLAB THICKNESS	5
3.1 The Mean Variations	5
3.2 Day-to-day Variations	10
4. VALIDATING EXISTING IONOSPHERIC MODELS	14
5. CONCLUSIONS AND RECOMMENDATIONS	16
6. REFERENCES	17
ACKNOWLEDGEMENTS	18
FIGURES	19
TABLE 1	39
APPENDIX	40



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IONOSPHERIC EQUIVALENT SLAB THICKNESS AND ITS MODELING APPLICATIONS

1. INTRODUCTION

There are a variety of ionospheric models currently in use or under development, each with its own approach to the problem of describing the global ionosphere. Theoretical models have grown greatly in sophistication over the course of this decade, both because of the vast increase in computing power, and because of the growth through data analyses in our qualitative understanding of the processes that occur in the ionosphere. One of the more well-known of these theoretical models was developed at Utah State University (e.g. Sojka and Schunk, 1985), where a time-dependent, three-dimensional, multi-ion numerical solution is achieved for the global F region. This model achieves good qualitative descriptions of the ionosphere (for example, in the equatorial anomaly region, the mid-latitude trough, and the winter anomaly). However, the quantitative agreement is not always good. While this model is being further validated and refined against new or existing data sets, and while these numerical experiments are important to our understanding of the global ionospheric morphology, the general scientific community continues to work with empirical or semi-empirical ionospheric models. This is not only due to their agreement with known data, but also for ease of numerical computation. And, in many cases, specification of the mean (or quiet condition) ionosphere is quite adequate.

The basic difference in emphasis between theoretical and semi-empirical models is that the former seek a self-consistent global solution, while the latter define the electron density profile at any given location and under any conditions. One such semi-empirical model is the International Reference Ionosphere, or IRI (Rawer, 1981). This combines empirical global maps of the profile peak parameters with analytic expressions for the shapes of each region of the ionosphere for the desired location, season and solar activity

conditions. The Bent (Llewellyn and Bent, 1973) model underwent a similar development, but utilized a different set of global maps and relied on simpler expressions for the profile shapes. One model under continued active development is the US Air Weather Service Ionospheric Conductivity and Electron Density, or ICED, model (Tascione et al., 1988). This model seeks to incorporate various processes or features of specific regions of the globe (such as the SLIM model, Anderson et al. (1987), at low latitudes) into a smoothly varying global model, and it is also designed to respond to real-time ground-based and satellite observations. This latter point, making use of all available real-time observations, is a very positive step in the field of ionospheric modeling.

For the reasons stated above, in the majority of ionospheric research today, specification of the electron density profile is the key, as this will drive the basic ionospheric model. The peak parameters (such as foF2 and h'F2) are generally obtained from empirical or semi-empirical global maps. These are simple numerical representations of observations and can, in principle, be constructed to any desired accuracy over a particular sounding network, according to the particular problem being addressed. The profile shape, however, is a complicated function of the neutral and plasma temperatures, ionic compositions, neutral winds, and therefore of the season, local time, location, level of solar and geomagnetic activity. Qualitatively, the effects of varying each of these parameters on the profile shape is reasonably well understood, but the problem of obtaining a reliable physical (or numerical) specification of the variations has not been achieved to date. There is a continued process of model validation and refinement.

The equivalent slab thickness is defined as the breadth (in km) of an ionosphere of uniform electron density equal to the peak density, N_{\max} . Functionally, $\tau = \text{TEC}/N_{\max}$, where $\text{TEC} = \int_0^{\infty} N_e(h) dh$, and it is a convenient one-parameter summary of the electron density profile. Indeed, it can be related to a variety of quantities of interest that effect

the overall profile shape. Apart from the intuitive relation to the F2 layer semi-thickness, various authors have proposed relations between τ and both neutral temperature and O^+/H^+ transition height (Titheridge, 1973), the scale height of atomic oxygen and drift motion (Furman and Prasad, 1973), and the mean gradient of electron temperature (Amayenc et al., 1971). In addition, τ is operationally a very useful parameter, as it allows one to make a simple conversion between foF2 and TEC.

The equivalent slab thickness is a parameter with largely unexplored applications in the field of ionospheric modeling. Firstly, it is a new database that should be used for model validation. Secondly, there is a different emphasis in studying τ . For example, validations based on foF2 indicate the models that successfully describe the layer peaks, but yield no information on the heights or the general profile shape. Validations that use observations of TEC largely assess the topside profile as anchored to the layer peak. While τ may not be easily interpreted in terms of neutral temperature, winds, or composition changes (though each of these effects may be anticipated), the variations are a good indication of how the broad structure of the electron density profile changes as a function of season, time of day and solar activity. Thus, studying τ does constitute a different way of utilizing the available databases of TEC and Nmax.

Describing the observed variations of τ at a reliable site is thus a worthwhile exercise, and this forms the core of this report. In subsequent sections, the database is introduced, the variations of τ are described both qualitatively and numerically, and modeling applications (validation and adjustments) are explored.

2. THE DATABASE

The bulk of the analysis contained in this report comes from mid-latitudes in the American sector. Measurements of TEC were obtained from Hamilton, MA, by observing the Faraday rotation of signals from the satellites ATS-3 and ATS-5. The 420 km sub-ionospheric point of this raypath lies at nearly the same latitude as an ionosonde located at Wallops Island, VA, but shifted by twenty minutes of local time.

Hourly values of τ have been calculated using the observed TEC (shifted by 15 minutes to be the LT equivalent over Wallops Island) and foF2 values. The sample of data consists of sparse observations from 1965 and 1967, and nearly complete observations from 1968-1986. This gives us access to two solar cycles of TEC, Nmax and τ . Possibly just as significant is the fact that the first cycle was of average strength, while the second was the second largest on record. Another significant point is that the TEC values have been verified by experienced personnel at AFGL, and should be regarded as reliable.

An important point to bear in mind is that slab thickness data combines the errors of two observational parameters, TEC and Nmax, each of which has some error of measurement. Also, each quantity is capable of interpretive error in the measurement. Misidentified layers on an ionogram will lead to an incorrect foF2 (and hence Nmax), and an incorrect identification of the $n\pi$ ambiguity (whether on a strip chart or by an automated data analysis routine) will mean systematically incorrect TEC values. In addition, there are physical differences in the measurements of foF2 and TEC. The former is deduced from vertical (or nearly) incidence on the ionosphere, while the latter is deduced from a slant path. The physical difference between the exact sub-ionospheric point and the location of the ionosonde will mean that TEC and Nmax will not necessarily relate to the same profile when horizontal gradients are large, such as in the period immediately following sunrise.

For all the above reasons, we expect the database of hourly τ values to be quite

noisy. Figure 1, showing the overplots of daily values of each parameter for a selected month, demonstrates this by showing the variation of τ to be the least smooth. Because of the noisiness of this database we have adopted a two-pronged attack to the problem of describing the variations of τ . Firstly, the mean variations are investigated. A reliable and representative mean is determined, dependencies on observed quantities are sought, and the variations are described, both qualitatively and numerically, through a simple coefficient-based model. It is this mean τ behavior that has immediate modeling applications, as the existing ionospheric models are only concerned with mean behavior. Secondly, some indications of the day-to-day variability are sought. Apart from a simple statistical analysis, and a correlation analysis between TEC, Nmax and τ , we also describe some of the systematic trends seen in τ in the periods immediately following geomagnetic storms, considered to be the extreme cases of day-to-day variability (see e.g. Mendillo, 1978).

3. DESCRIBING THE VARIATIONS OF SLAB THICKNESS

This section of the report is divided into two subsections, concerning the mean and day-to-day variations of the equivalent slab thickness parameter, τ .

3.1 The Mean Variations

As described above, the database of hourly slab thickness values is noisy (more so than each of TEC or Nmax individually), and thus an appropriate mean needs to be carefully defined. As is usual practice in ionospheric work, we are concerned with monthly mean behavior (the time scale in the existing semi-empirical models). How then do we define a 'mean' for each hourly value over the course of the month that is a true representation of the data? The desirable criteria for such a mean are that it varies smoothly over the 24 hourly values for each month, that it is not unduly influenced by individual extreme (and possibly erroneous) values, but that it does reflect general trends in the hourly values. The arithmetic mean was tested first, and was seen to be strongly influenced by outlying values,

leading in turn to a jagged daily variation. In an attempt to remove the extreme cases of day-to-day variation, an arithmetic mean was also evaluated for only those days that were geomagnetically quiet ($A_p < 10$). However, this quiet mean was still influenced by outliers. The median values were more stable, but were not influenced by extended tails of the distribution of hourly values. The most successful mean tested was the trimmed mean. This is simply the arithmetic mean of the central 50% of the values in the distribution. Visually, this parameter showed the smoothest overall variation, and the most appropriate response to different distributions of hourly values.

Having now defined the mean values, it is a good place to describe the apparent variations of τ and to put them into perspective. Figure 2 shows a three-dimensional representation of the trimmed mean values of τ for typical low and high solar activity years. The diurnal variation (good examples of which are shown in Figure 3) is clearly different from that of TEC and N_{max} . Indeed, TEC and N_{max} are quite highly correlated (see the next subsection) and τ therefore highlights the differences. Broadly speaking, the nighttime τ values are far less variable (in terms of an annual variation) than the daytime values. In particular, daytime τ values are higher in summer than winter, with summer daytime values being higher than the nighttime values and the reverse being the case in winter. The diurnal variation in equinoctial months is quite small. The highest values (excluding the less reliable transition period around sunrise) are seen in winter months, around midnight, at times of low solar activity. This tells us that the electron density profiles are flattest at these times. According to Buonsanto et al. (1979) this occurs to a greater extent at higher latitudes (Goose Bay, Canada - $L=4$). This all suggests that the layer peak has a far more rapid decay than the TEC after sunset during winter, at low activity and at higher latitudes and flatter profiles result. Titheridge (1973) suggests that this increase in τ relates to a lowering of the O^+/H^+ transition height. The profiles attain a more normal shape (and thickness) before dawn. The higher slab thickness values attained during summer

days could be interpreted in terms of greater scale heights occurring in the topside region during times of maximum observed TEC (increases in ionization being more likely to occur in the topside than the layer peak), and would be related to the higher electron and ion temperatures occurring then. The generally clear trend to increase τ with increasing solar activity (comparing the lower and upper panels in Figure 2) also reflects increases in the topside.

The next step is to determine a convenient numerical (coefficient-based) representation for the mean values of τ from the Hamilton/Wallops Island site. As the diurnal variation appeared to dominate, this was the first variation to be described. Various numerical techniques were considered for describing the diurnal variation. Polynomial fits were not accurate (up to a reasonable order) and are not intrinsically periodic. Cubic splines are generally a smooth and accurate representation of data but are more useful for interpolation than for convenient numerical summaries, and can be unreliable when individual data points are suspect. Fourier analysis was the logical choice for describing this generally smooth and periodic database (the monthly trimmed means). The order of the fit was optimized both with respect to the residuals of the fit and with respect to the smooth appearance of the resulting diurnal curves, and overall, 4th order Fourier analysis yielded the best results. Furthermore, a Weighted Fourier analysis was used in an attempt to improve the reliability of the representation. In any given month, weights were assigned to each of the 24 hourly mean values that reflected the level of confidence in that value. These weights were inversely proportional to the quartile range of the individual hourly values, so that the mean of a widely spread distribution of values gets little weight. In addition, data obtained during sunrise and sunset periods were further downweighted to avoid possibly erroneous values obtained when horizontal gradients were large. Weights at these times were further reduced by a factor of 10. Figure 4 contrasts a raw Fourier analysis with a Weighted Fourier analysis for the same set of data. In the majority of cases, there is little

difference between the two. The only systematic difference is that a peak in mean τ that is often seen around dawn hours does not appear in the Weighted Fourier representation. The justification for this approach is that it would be difficult to describe reliably such a feature when it is often denoted by only one point (when hourly data is used). Further, to devote a large effort to modeling a peak in τ at 0500 LT or 0600 LT is largely pointless, as the ionosphere is changing rapidly and the mean ionospheric models are all less reliable anyway. Yet, the presence of this dawn peak is also worthy of comment. While it has been neglected in our numerical model, it is a persistent feature. Indeed, it is a common feature in studies of slab thickness, having been observed in Wales (Hajeb-Hosseinih and Kersley, 1975), New Zealand (Titheridge, 1973), Australia (Essex, 1978) and India (e.g. Prasad et al., 1987), as well as farther north in the American sector (Buonsanto et al., 1979). Such consistency would certainly indicate a real feature. Evans (1968) and Titheridge (1973) identified this feature with an enhanced loss mechanism near the layer peak prior to dawn. Indeed, when one looks at individual months where this peak is pronounced, the rise in τ relates to a fall in N_{max} greater than the fall in TEC.

Having described the diurnal variations by this Weighted Fourier analysis, the dependencies of τ on solar and geomagnetic activity were sought. In particular, the variation of τ with respect to monthly mean sunspot number (a ready measure of solar activity) and monthly mean Ap index (geomagnetic activity) was studied. A linear relationship with respect to sunspot number was deduced. Overall, the correlation coefficient was around 0.4. While this indicates significant departures from a linear dependence, it also means that inclusion of this simple dependence does significantly reduce the overall residuals. There was no justification for considering higher order terms than first. It was noted that there was some diurnal modulation in the degree of correlation between τ and sunspot number, with the greater correlation generally occurring during the day and significantly less correlation occurring at night, especially around dawn. Overall, no

dependence on monthly mean magnetic activity could be found. The correlation coefficient in this case was 0.04. This was not a surprising result, as monthly mean magnetic activity is not a meaningful quantity. Day-to-day variations are enhanced during times of geomagnetic storms and so day-to-day effects would be expected, but it is not obvious that these effects would carry over to monthly means. Kersley and Hajeb-Hosseini (1976) did report a geomagnetic dependence in the slab thickness over Wales (this was also described in their earlier unpublished report). However, this trend was probably a chance result. The database extended over less than one solar cycle and the apparent dependence on mean A_p values hinged on several months from 1973 and 1974 of high mean A_p . The same trends towards higher τ in these particular months were in fact seen in our Hamilton database, but no correlation was seen at Hamilton as the effect simply did not last for the whole two solar cycles. It thus appears that the smaller sample size led to an apparent correlation with monthly mean A_p in the case of the Welsh data.

Finally, the annual variations of the model were described. The derived coefficients of the diurnal and solar cycle variations were examined as a function of month (examples are seen in Figure 5). The plots indicated that a 1st order Fourier series would be a good representation of the annual variations. There was no indication of any 2nd or higher order terms. Coefficients not well-defined by a 1st order analysis were simply too noisy to be described accurately by any method.

The coefficients for this simple mid-latitude slab thickness model are given in Table 1, and a sample Fortran routine to generate predicted values of τ using these coefficients is listed in the Appendix. The rms errors of this model, with respect to the original trimmed means, is 23 km, or less than 10% of the total sample average of 277 km (with corresponding σ of 71 km). On a month-by-month basis, the errors are normally distributed (that is, there is no bias in the rms due to individual poor months), and no residual

dependency on a monthly parameter could be detected.

The overall variations included in this simple model are shown in Figure 6 in the form of Figure 1. The smoothness and reliability of the model can be gauged by comparing these two figures. Figure 7 shows the predictions of the model of Hajeb-Hosseinih and Kersley (1975), ignoring the probably spurious geomagnetic dependence. Apart from the Hajeb-Hosseinih and Kersley model predicting slightly higher values the two models are in very good agreement, and so it could be expected that at least over the 40° to 50° range, that τ is not a strong function of either latitude or longitude.

3.2 Day-to-day Variations

In this section we will describe both the results of a correlation analysis of the daily TEC, Nmax and τ values in our database, and some preliminary results from an investigation of the ionospheric effects of geomagnetic storms (regarded as the extreme cases of day-to-day variability).

We begin with the correlation analysis. For this study, we are required to consider distributions of each of the three variables, and to investigate the degree to which a departure from the mean in one variable is associated with departures from the mean in the others. Perfectly correlated variables are distinguished by a one σ deviation in one variable being associated with a one σ deviation in the other, and has a correlation coefficient of 1.0. A correlation coefficient of -1.0 denotes anti-correlation, while 0.0 would show that no correlation is present between the two variables. We have selected a sample size of one month for each hourly value, and have deduced correlation coefficients for each month-hour sample throughout the database. A histogram of the correlation coefficients is shown in Figure 8. As expected, TEC and foF2 (and therefore, Nmax) are quite highly correlated. The distribution of values peaks around 0.9 and there are only a small number of samples with correlation coefficients less than 0.5. Also worth noting, is the distribution of values

for τ and foF2. There is a tendency for these values to be anti-correlated, with a peak value of around -0.7 to -0.8. This anti-correlation is significant in terms of developing a daily 'adjustment' to the mean slab thickness model. In a real-time case a value of foF2 may be available, and a real-time estimate to τ could be desired before predicting TEC. If the departure from the mean foF2 value is used in combination with an assumed anti-correlation with τ , and the resulting τ used to estimate the real-time TEC, this TEC estimate will be essentially the same value deduced from mean values of both foF2 and τ . That is, assuming a perfect anti-correlation tends to wipe out the known departure rather than to make use of it. Similarly, if one uses 'daily' estimates of τ in this fashion to generate daily values of TEC from daily foF2, then the predicted day-to-day variability in TEC will be greatly underestimated (that the anti-correlation is not perfect means that the departures will not exactly cancel). This does not mean that a model of daily τ or TEC values cannot be found, or that a description of the day-to-day variability cannot be obtained. It simply means that a simple statistical analysis does not provide the answers. The place to begin a proper investigation of day-to-day variability is in the periods immediately following geomagnetic storms where the variability is greatest.

The behavior of TEC (and therefore Nmax, the two being well correlated) during geomagnetic storm periods is well-known. Mendillo (1978) used data from a chain of stations at American sector longitudes to study and compare the effects at different latitudes, and used the observed variations to deduce the underlying physical processes. Mendillo described the trends with latitude and season, and studied some selected storm periods in greater detail. In this report, some preliminary results for the ionospheric response to geomagnetic storms, for each of TEC, Nmax and τ , from our two solar cycle database are presented. When studying daily responses, there are a couple of points in keep in mind. Firstly, the departures from mean conditions are desired. Mendillo (1978) considered the percentage departures from the monthly means and we will base our work

on the same parameter. Secondly, some care is required to investigate the departures from normal conditions on a storm-by-storm basis. For one thing, the ionosphere can be sufficiently disturbed as to disrupt the continuity of data sampling during storm periods. Also, actual hourly data will be noisier than monthly means (especially for τ) and will have individual spurious values, and thus some form of data screening should be implemented prior to studies of individual storms.

For now, however, we simply wish to present some results for two solar cycles of Hamilton TEC, N_{\max} and τ storm-related departures. To date, the data has not been shifted in storm-days in the manner of Mendillo (1978). Figure 9 shows the storm departures averaged over all storms in the period. The same trends seen at Hamilton for a smaller sample by Mendillo are seen here. Figures 10 and 11 show the effects of limiting the storms considered in these averages according to a minimum value of A_p (as deduced from 3-hourly K_p). The effects of increasing A_p are clearly seen, and thus a dependence on A_p for both storm-time departures and day-to-day variability would be expected. Figures 12 and 13 demonstrate the overall averages (all storms) of departures during summer and winter months. It was expected from the discussion of Mendillo (1978), that the night-time enhancement in τ would become more significant at lower latitudes (in this case, Hamilton) during the winter months, and this is seen in the average winter patterns shown here for all but the first night.

In all these storm-departure figures, one consistent feature is that τ is enhanced during times of geomagnetic disturbance. That is, the electron density profile remains flatter than normal, both in the TEC enhancement (filling in of the topside) and depletion (enhanced loss in the layer peak) phases. Mendillo (1978) relates the daytime increases in τ to the heating processes that cause enhancements in the plasma scale height. Another noticeable feature in the response in τ is that the variations are smaller than either TEC or N_{\max} ,

and that on a storm-by-storm basis, the response is not as smooth as for TEC and Nmax. This reflects the secondary nature of the τ variations due to the generally high degree of correlation between TEC and Nmax, as well as the fact that less data is available for τ than either TEC or Nmax (as both are required before τ can be defined).

It is important to recall that storms are not all of the same character and responses vary significantly from one storm to the next. Indeed, a 20% average departure may correspond to a 60% departure for $\frac{1}{3}$ of the cases and no departure elsewhere. It is more useful to correlate the storms where the 60% effect occurs than to model a 20% term overall. The next logical step would be to characterize the storms in terms of the observed variations and to correlate these with season, solar activity, maximum Ap, onset time and so on.

4. VALIDATING EXISTING IONOSPHERIC MODELS

The availability of a mid-latitude mean τ model makes two tasks immediately possible. The first is to convert a database of foF2 values from a network of mid-latitude ionosondes into a database of TEC values, to be used for model validation. The second is to use the currently available profile models to predict τ at the location where it is known (Hamilton), to further validate the models.

The first of these tasks was a project coordinated at AFGL, involving data converted from foF2 to TEC at the Institute for Telecommunication Sciences, Boulder, Colorado using the simple mean model of τ developed here at Boston University, with personnel at Computational Physics Inc., Newton, MA, making comparisons of the derived TEC values. This work is currently being prepared as a report (Klobuchar et al., 1989), but it is worth describing a few key points here, for completeness. Two of the models tested, IRI (Rawer, 1981) and FAIM (Anderson et al., 1989), were consistently poor predictors of the deduced TEC. The Bent (Llewellyn and Bent, 1973), Damon-Hartranft (Damon and Hartranft, 1970), and ICED (Tascione et al., 1988) models were all more successful, typically describing the TEC to around one σ of the apparent day-to-day variation. It was noted that a significant portion of the errors in the deduced TEC could be related to the predicted foF2 in each model not always being in good agreement with the observed monthly median foF2.

Here at Boston University, available empirical electron density profile models have been used to predict the mean values of τ at Hamilton, MA. Some comparisons showed that none of the models tested had τ values that were strong functions of latitude or longitude in this mid-latitude range, and therefore these comparisons are equally valid at other mid-latitude locations. Estimates of τ have been generated from each of the IRI, FAIM, Bent and Damon-Hartranft models, and 3-D plots of these are shown in Figures 14-17. As was

the case for the TEC comparisons, the IRI and FAIM models are an inadequate description of τ . In the IRI, there is little diurnal or seasonal variation, and an exaggerated variation with solar activity. FAIM showed some diurnal variation, but little seasonal and solar cycle variation. The Bent model τ values were of consistently different character to the observed values, and so it was a little surprising that the derived TEC values should have been quite comparable. The Damon-Hartranft model showed the intrinsic variation of τ that was most like the Hamilton observed values, but contained somewhat larger diurnal modulation.

As both the Bent and Damon-Hartranft profile models were close overall in TEC, and of simple enough formulation to be changed, some attempts were made to adjust each of these models to match the observed Hamilton τ .

The Bent model profile consists of five regions, and is described by a bottomside bi-parabola, topside parabola, and three topside exponential layers. The parabolic layers both yielded slab thickness estimates that were proportional to the layer semi-thickness, y_m , and these were largely responsible for the daytime variations in τ . The first adjustment made was therefore to replace the tabulated values of y_m with values that were proportional to observed values at Hamilton. This improved the agreement in the afternoon and evening. Nighttime contributions were dominated by the topside exponentials, and large values between midnight and dawn could be remedied by reducing the scale height of these exponentials in certain cases. The adjusted Bent model τ values are shown in Figure 18. While agreement is still not ideal (both because the variations are still quite different and because of the circularity of implicitly using observed values to reproduce observed values) there is considerable improvement over the original Bent model.

The Damon-Hartranft model consists of only four layers; E, F1, bottomside F2 and topside F2. The first three are Chapman-type layers, while the topside F2 is described by an exponential layer of increasing scale height. In terms of τ , the contribution from the

topside dominated. However, there was an unexpectedly large contribution from the F1 layer (over 20% in some cases) that peaked during the afternoon when the predicted value of τ was so much higher than that observed. Without this F1 layer, the Damon-Hartranft model τ values are as shown in Figure 19. This is the best agreement of any 'model' with the Hamilton slab thickness, and would therefore be the first to be recommended for future use based on these comparisons.

5. CONCLUSIONS AND RECOMMENDATIONS

The behavior of the equivalent slab thickness has been investigated at a mid-latitude site, and had been described by a simple numerical model. The usefulness of this model at other locations depends on the slowly-varying nature of τ , as deduced from comparisons made either side of the Atlantic Ocean. Given the desirability of having a global model of τ , both physically and operationally, it would be useful to further investigate the variations of τ at other locations. It would also be desirable to obtain TEC measurements from other independent sources, as both the Hamilton and Wales TEC data was validated in the same way; relying on comparisons of derived τ values to correctly identify the $n\pi$ ambiguity. Removing any possible circularity of this procedure would be a major step in correctly defining the real variations of slab thickness.

Deriving the real day-to-day variations also remains a desirable goal. Characterizing the responses following geomagnetic storms will be a key step in pinpointing the physical processes that are occurring, as well as making possible some functional model of day-to-day variations. It is through a method such as this that the most reliable real-time estimates of TEC (or range error) will be achieved.

REFERENCES

- Amayenc, P., Bertin, F. and Papet-Lepine, J. (1971) "An empirical relationship between ionospheric equivalent slab thickness and mean gradient of the electron temperature in the F region", *Plan. Space Sci.*, vol. 19, p. 1313.
- Anderson, D.N., Mendillo, M. and Herniter, B. (1987) "A semi-empirical low-latitude ionospheric model", *Radio Science*, vol. 22, p. 292.
- Anderson, D.N., Forbes, J.M. and Codrescu, M. (1987) "A fully analytic, low- and middle-latitude ionospheric model", *J.G.R.*, vol. 94, p. 1520.
- Buonsanto, M.J., Mendillo, M. and Klobuchar, J.A. (1979) "The ionosphere at L=4: average behavior and the response to geomagnetic storms", *Ann. Geophys.*, vol. 35, p. 15.
- Damon, T.D. and Hartranft, F.R. (1970) "Ionospheric electron density profile model", AESC Tech. Memo 70-3, 4WWg, July 1970.
- Essex, E.A. (1978) "Ionospheric total content at southern mid-latitudes during 1971-74", *J. Atmos. Terr. Phys.*, vol. 40, p. 1019.
- Evans, J.V. (1968) "Sunrise behavior of the F layer at mid-latitudes", *J.G.R.*, vol. 73, p. 3489.
- Furman, D.R. and Prasad, S.S. (1973) "Ionospheric slab thickness: Its relation to temperature and dynamics", *J.G.R.*, vol. 78, p. 5837.
- Hajeb-Hosseini, H. and Kersley, L. (1975) "Analysis of satellite recordings. Studies of ionospheric slab thickness", Interim Scientific Report, AFOSR-72-2267, Air Force Cambridge Research Lab., Bedford, MA, U.S.A. **AFCRL-TR-75-0521, ADA017715**
- Kersley, L. and Hajeb-Hosseini, H. (1976) "The dependence of ionospheric slab thickness on geomagnetic activity", *J. Atmos. Terr. Phys.*, vol. 38, p. 1357.
- Llewellyn, S.K. and Bent, R.B. (1973) "Documentation and description of the Bent

ionospheric model", Report AFCRL-TR-73-0657, Air Force Cambridge Research Lab., Bedford, MA, U.S.A., AD772733

Mendillo, M. (1978) "Behavior of the ionospheric F-region during geomagnetic storms", Technical Report AFGL-TR-78-0092(II), Air Force Geophysics Lab., Bedford, MA, U.S.A., ADA056978

Prasad, D.S.V.V.D., Niranjan, K. and Rama Rao, P.V.S. (1987) "TEC and equivalent slab thickness at low and mid-latitudes- A comparative study", Indian Journal of Radio and Space Physics, vol. 16, p. 295.

Rawer, K. (1981) "International Reference Ionosphere- IRI 79", Report UAG-82, J.V. Lincoln and R. Conkright eds., World Data Center A, Boulder, CO, U.S.A.

Sojka, J.J. and Schunk, R.W. (1985) "A theoretical study of the global F region for June solstice, solar maximum and low magnetic activity", J.G.R., vol. 90, p 5285.

Tascione, T.F., Kroehl, H.W., Creiger, R., Freeman Jr., J.W., Wolf, R.A., Spiro, R.W., Hilmer, R.V., Shade, J.W., and Hausman, B.A. (1988) "New ionospheric and magnetospheric specification models", Radio Science, vol. 23, p211.

Titheridge, J.E. (1973) "The slab thickness of the mid-latitude ionosphere", Plan. Space Sci., vol. 21, p. 1775.

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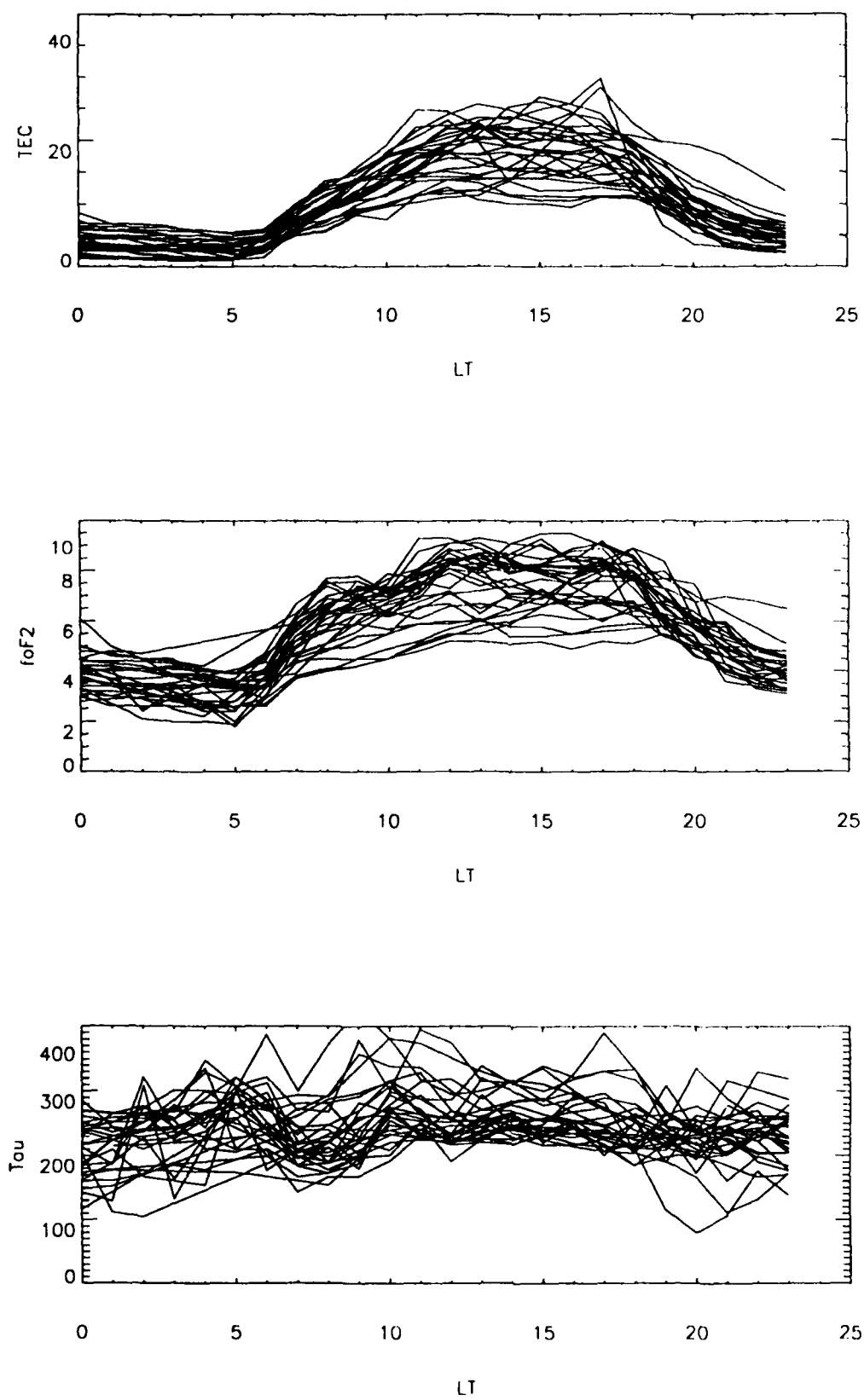


Figure 1. Daily overplots of TEC, foF2 and slab thickness for March 1973.

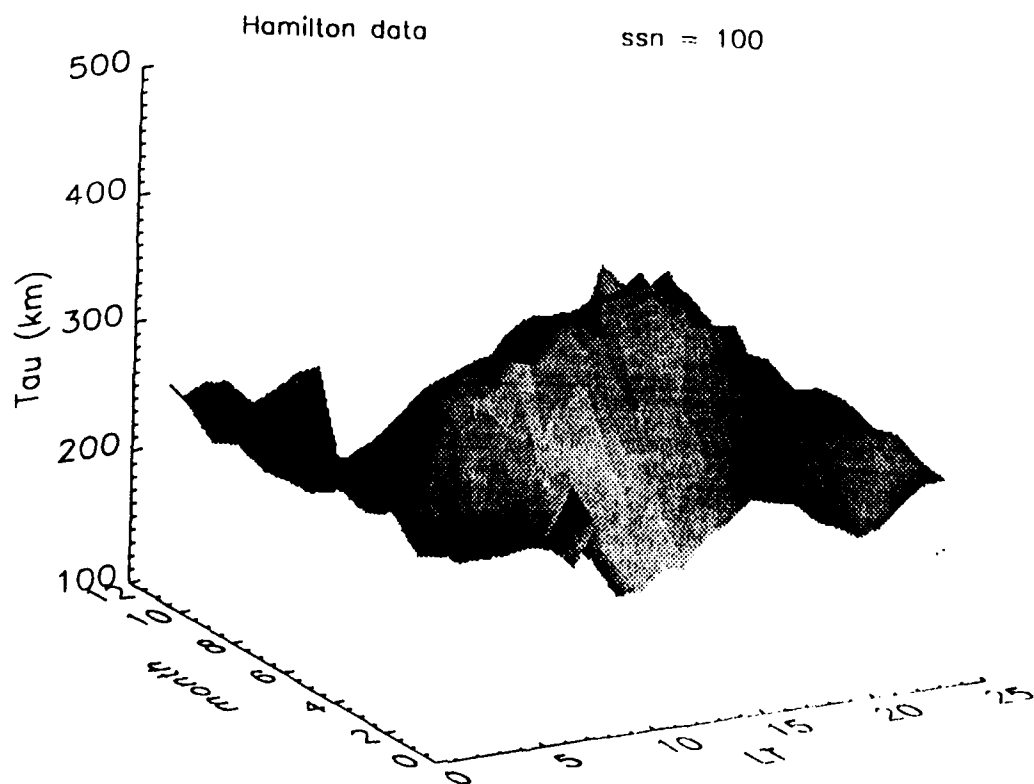
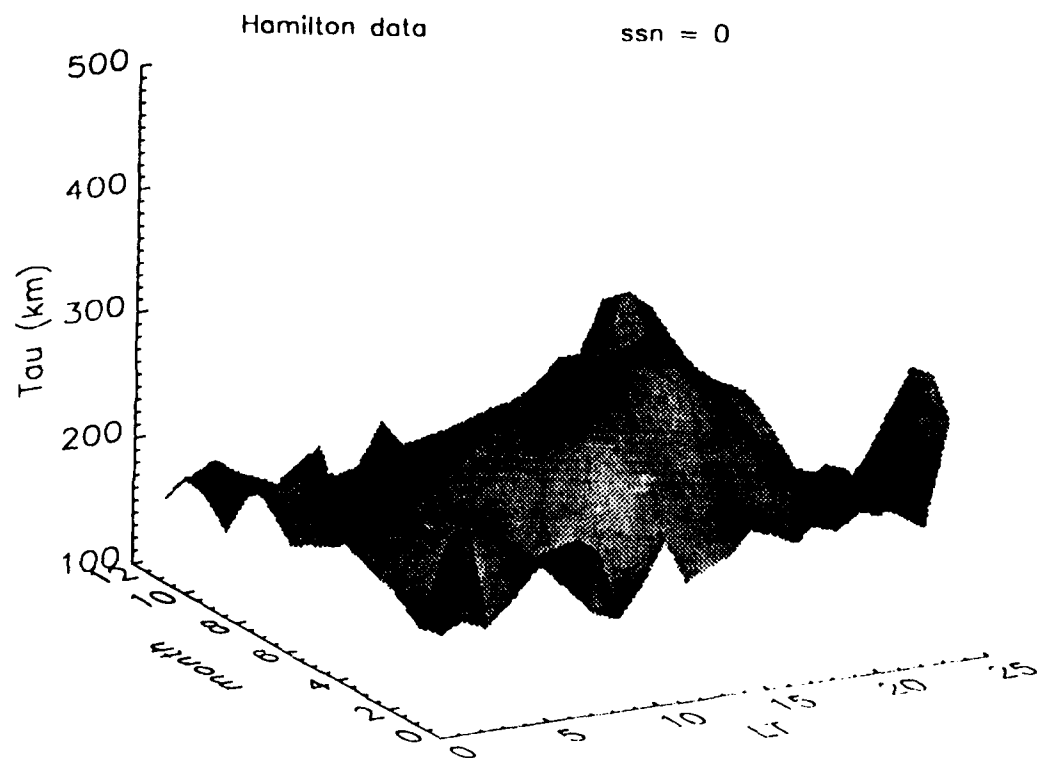


Figure 2. The variations of slab thickness over Hamilton for typical years.

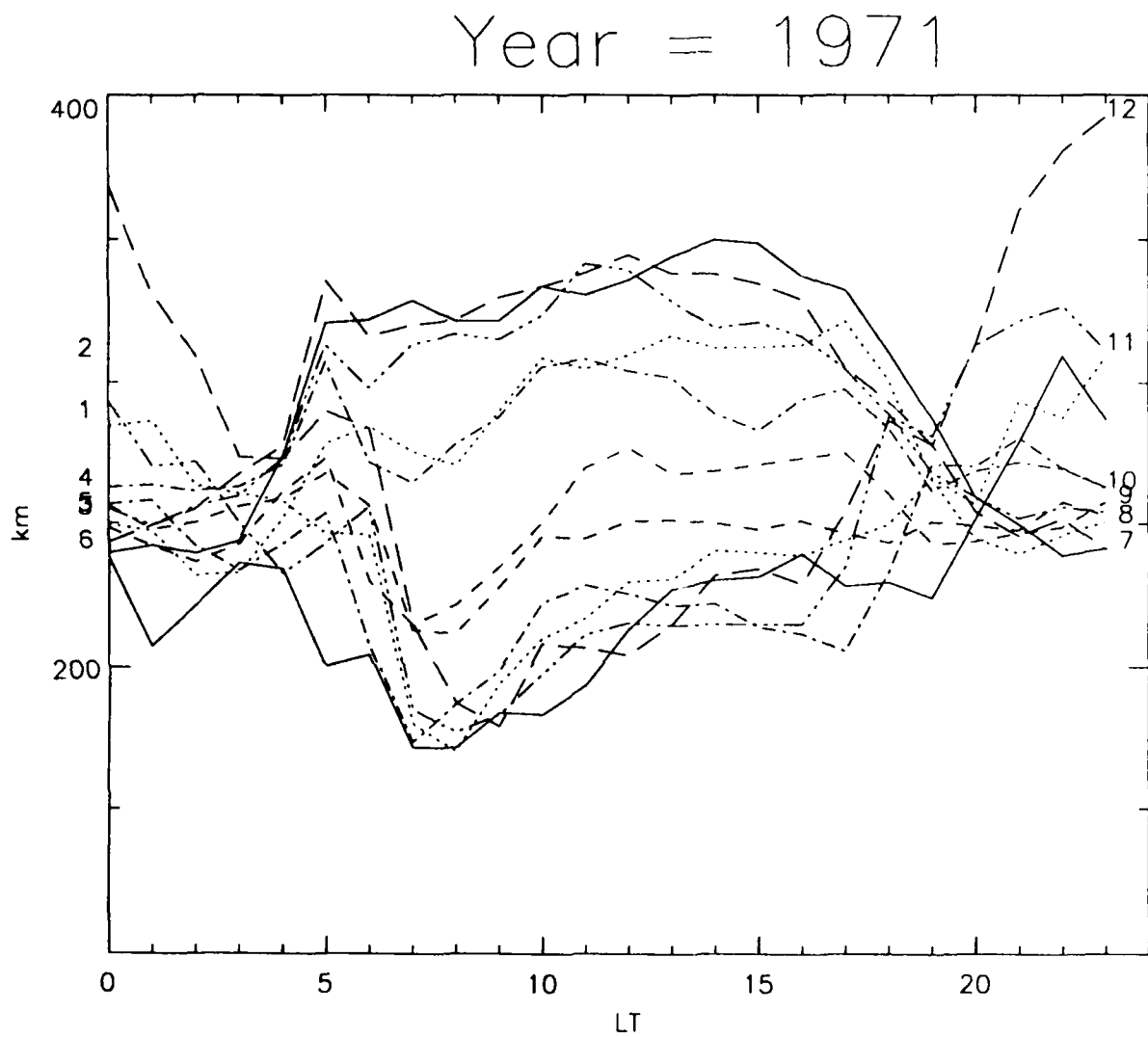


Figure 3. Diurnal variations of mean slab thickness for each month of 1971, with the months as labeled. Six line styles have been used, each style denoting two months spaced six months apart (e.g. January and July).

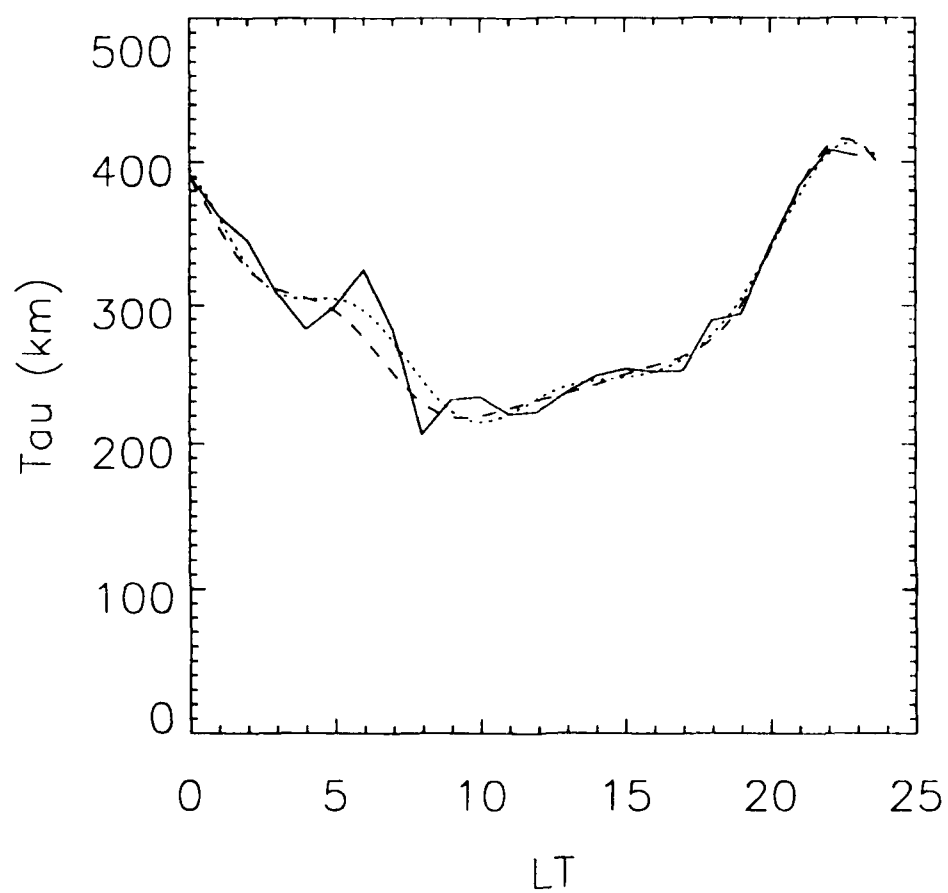


Figure 4. A comparison of fits derived from a normal (dotted line) and Weighted (dashed line) Fourier analysis on slab thickness data (solid line).

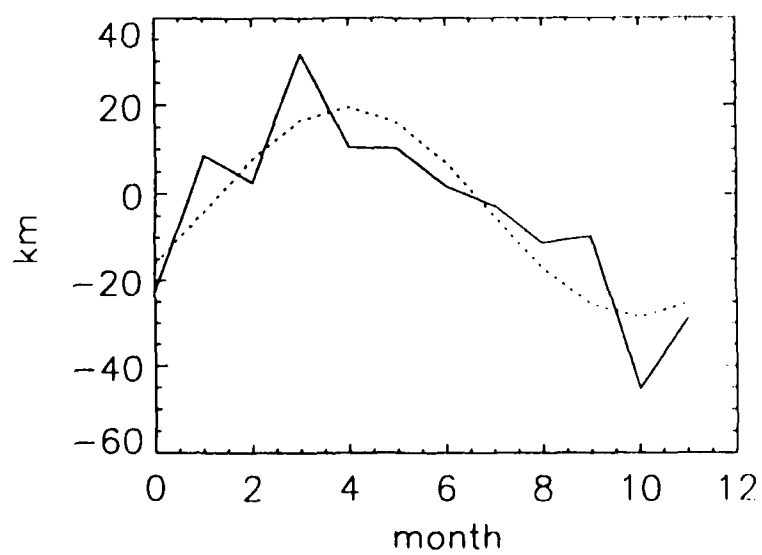
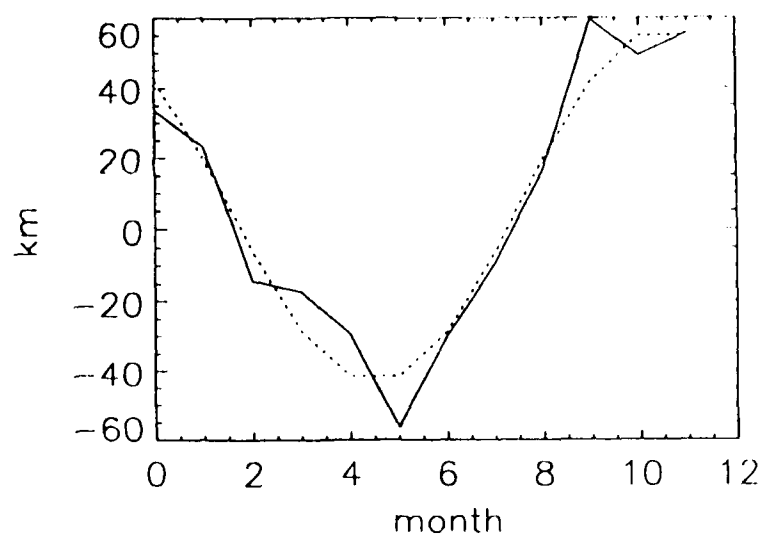


Figure 5. Typical annual variations of sunspot number-diurnal coefficients (solid lines) compared with a first order annual Fourier fit (dotted lines).

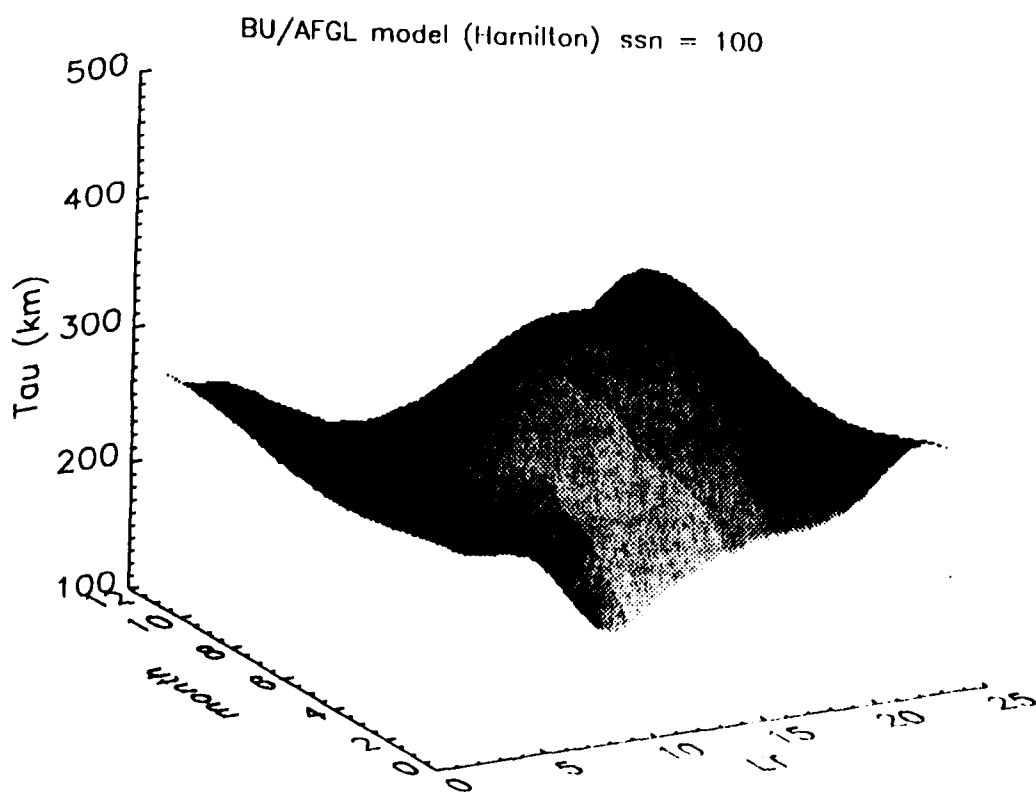
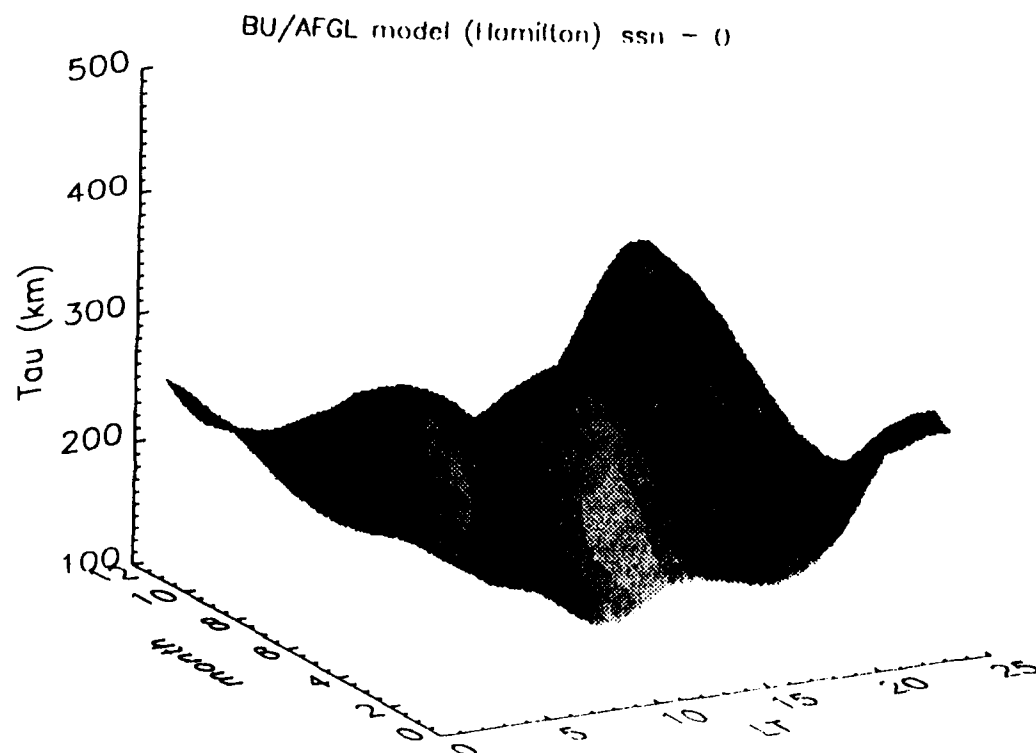


Figure 6. The variations of the derived numerical model of slab thickness over Hamilton.

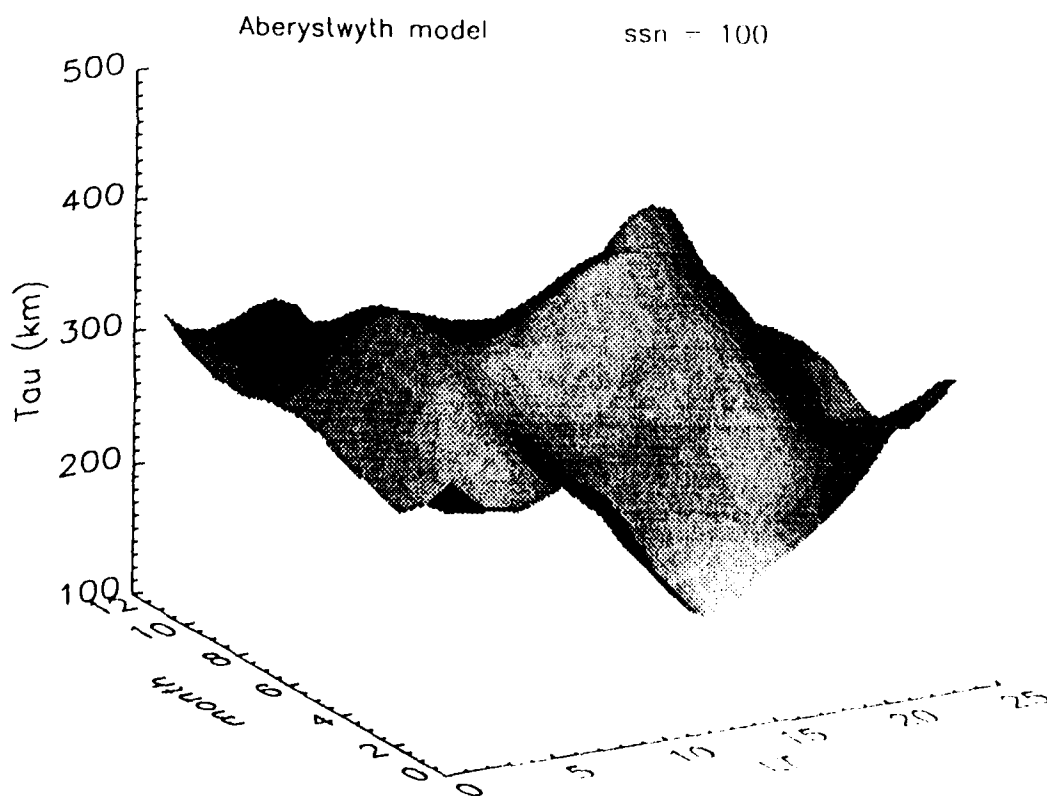
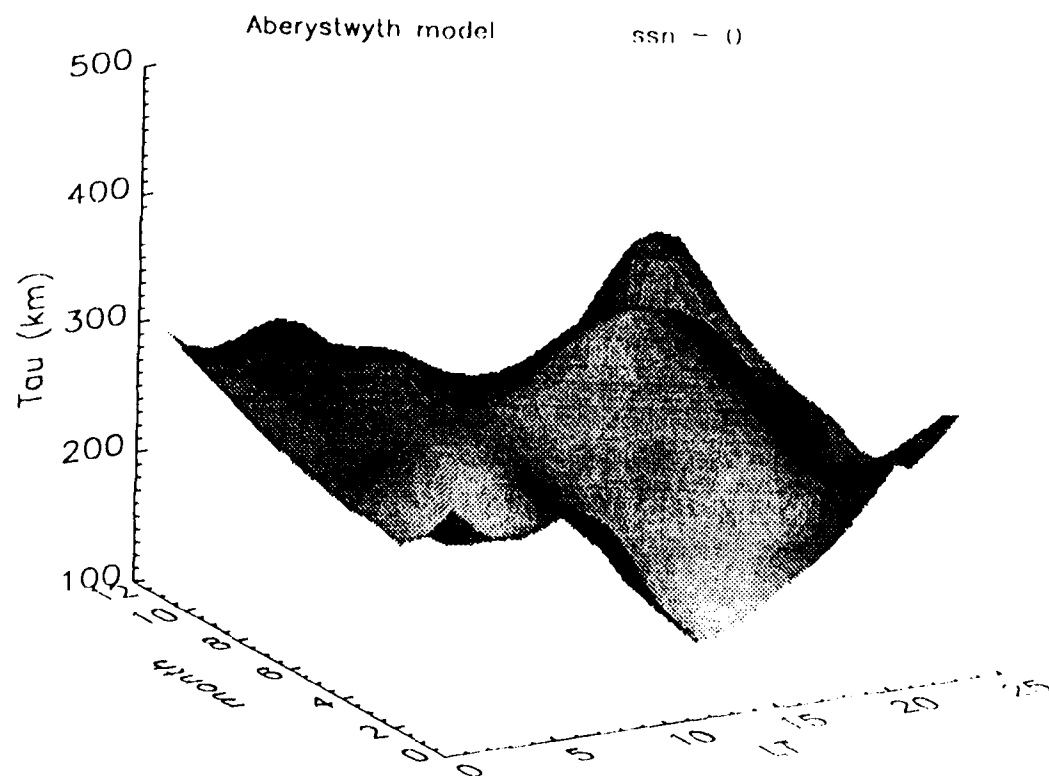


Figure 7. The variations of the slab thickness model of Hajeb-Hosseini and Kersley, over Aberystwyth, Wales.

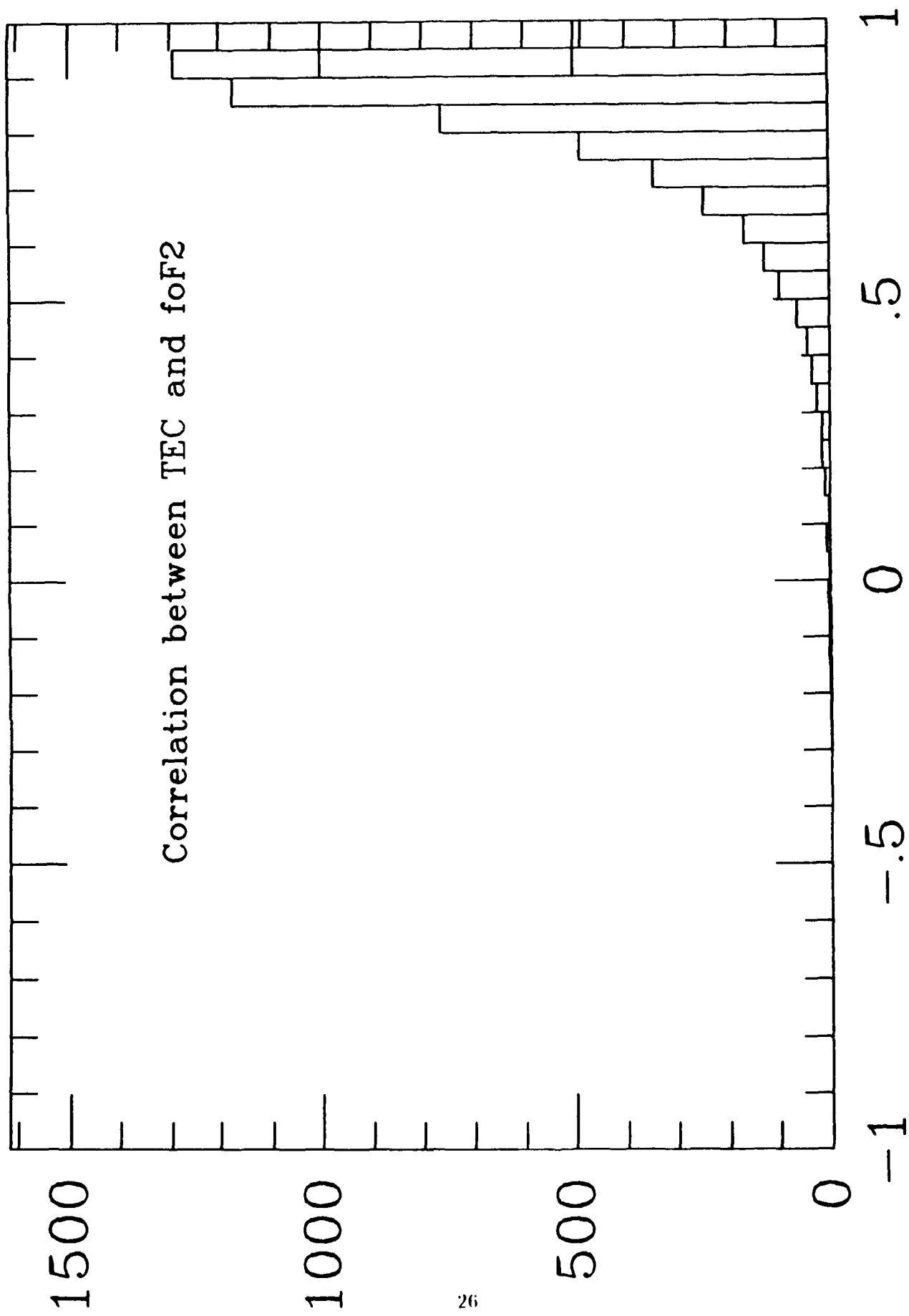


Figure 8a. A histogram of correlation coefficients between TEC and foF2.

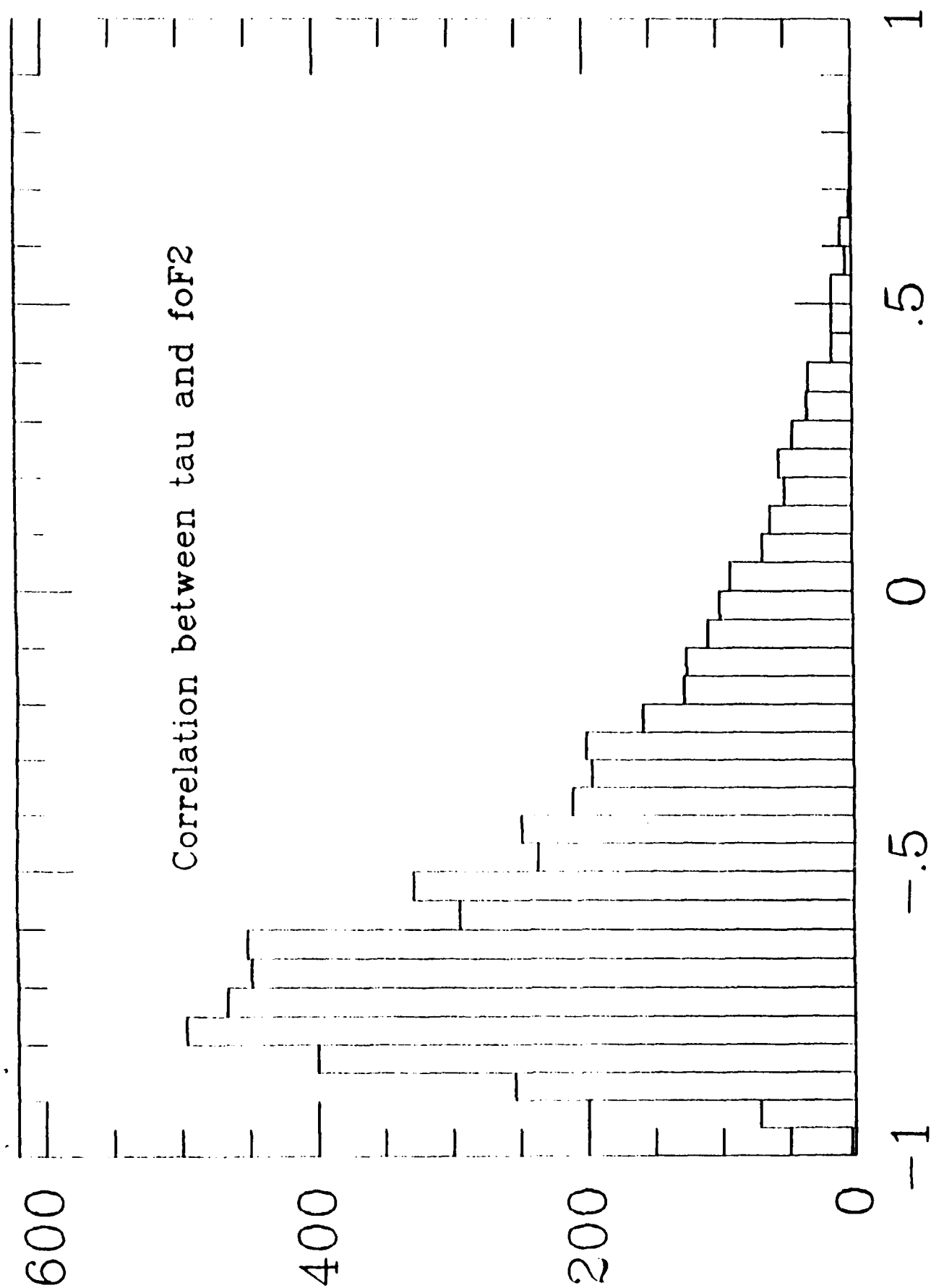


Figure 8b. A histogram of correlation coefficients between slab thickness and foF2.

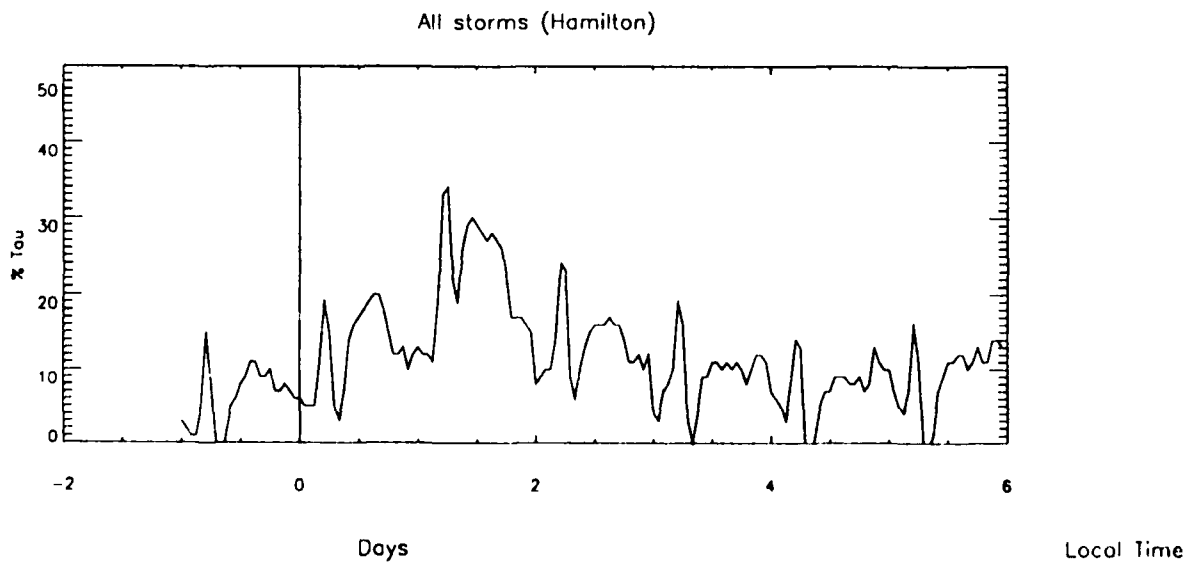
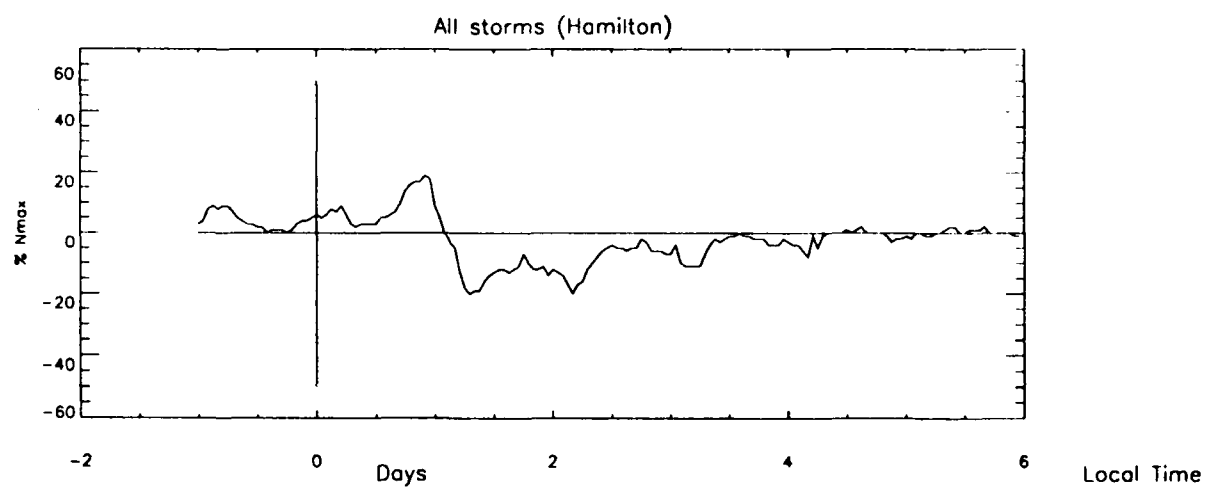
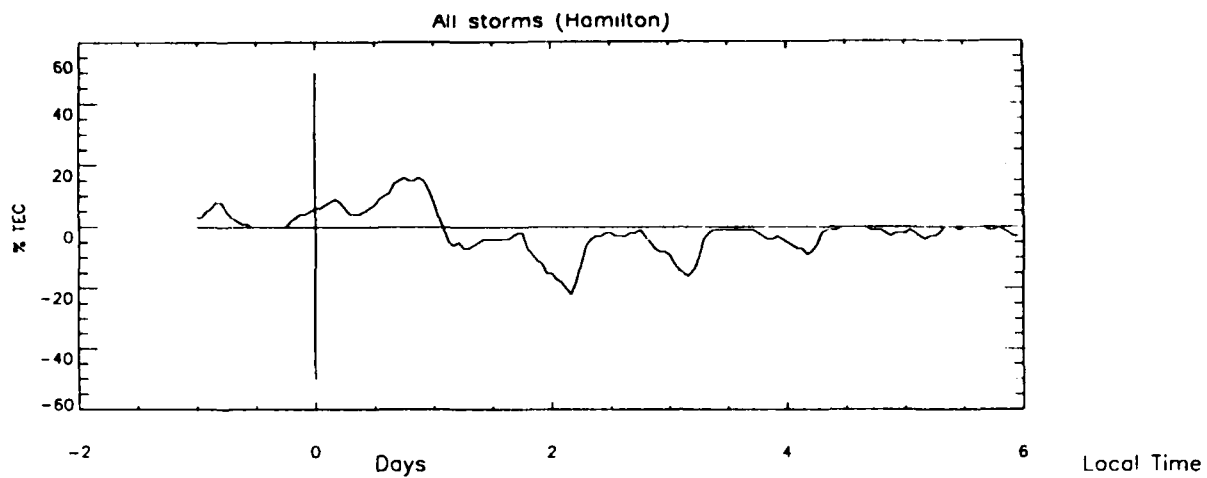


Figure 9. Average storm patterns for Hamilton, showing the relative percentage enhancements and depletions in TEC, Nmax, and slab thickness in the days following the storm.

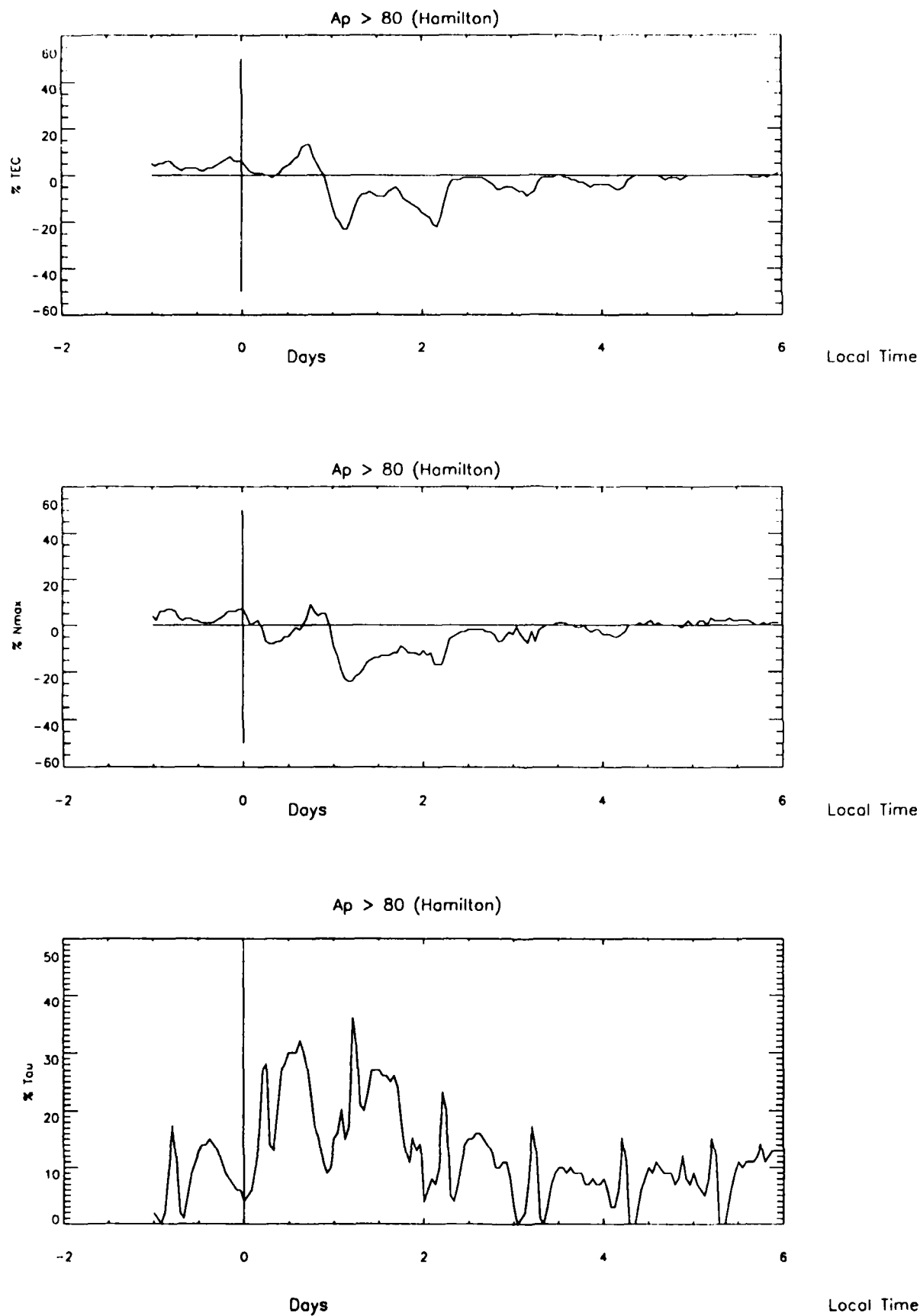


Figure 10. Average storm patterns, as in Figure 9, for a sample of storms of peak Ap 80

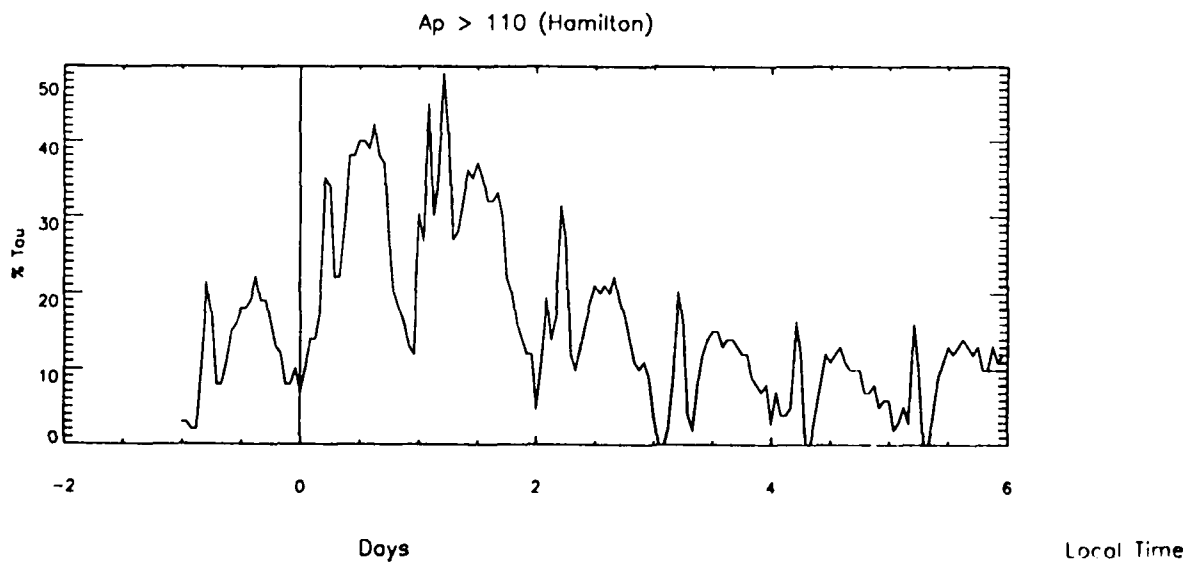
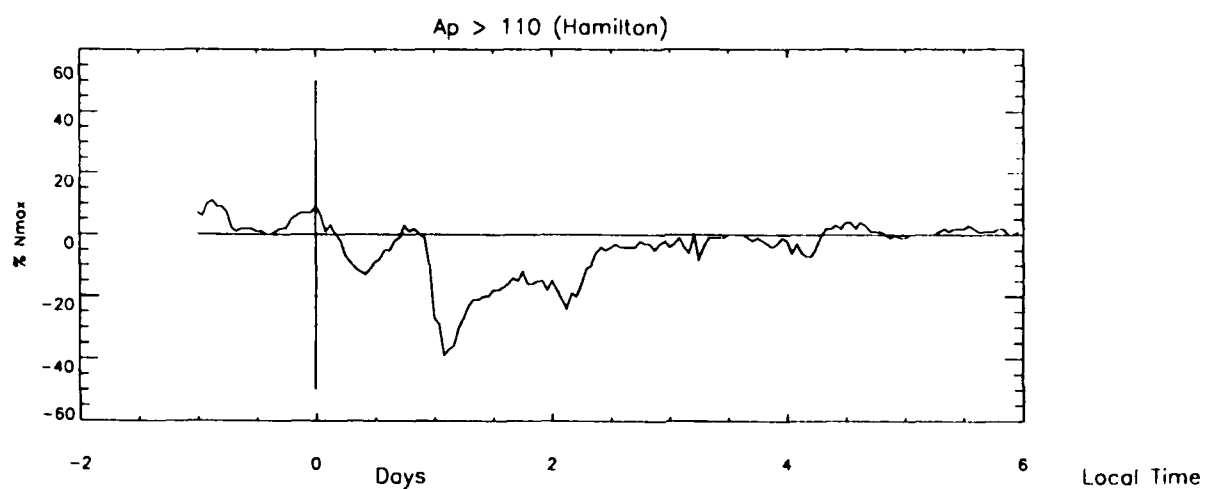
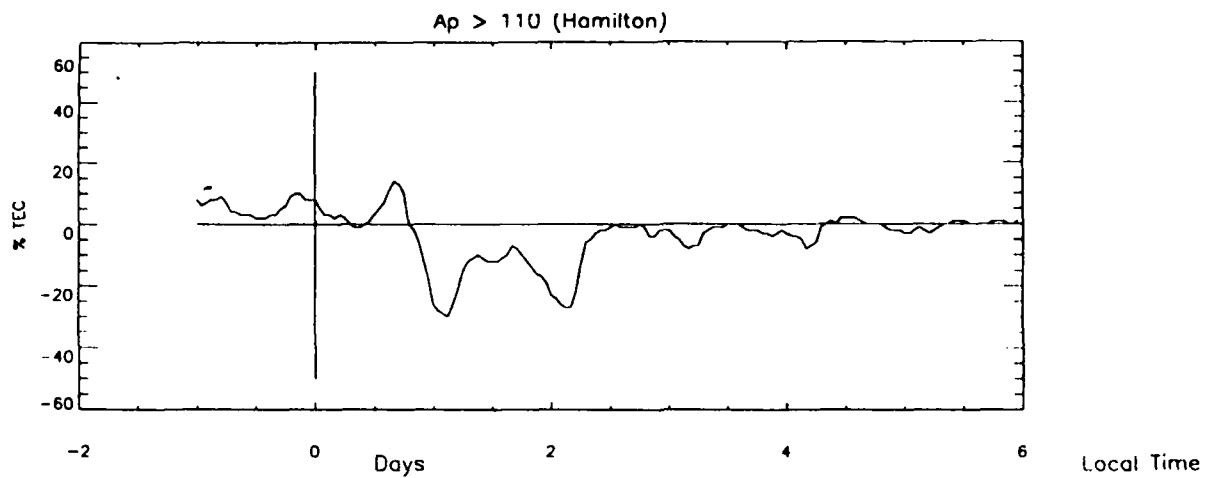


Figure 11. Average storm patterns, as in Figure 9, for a sample of storms of peak Ap 110

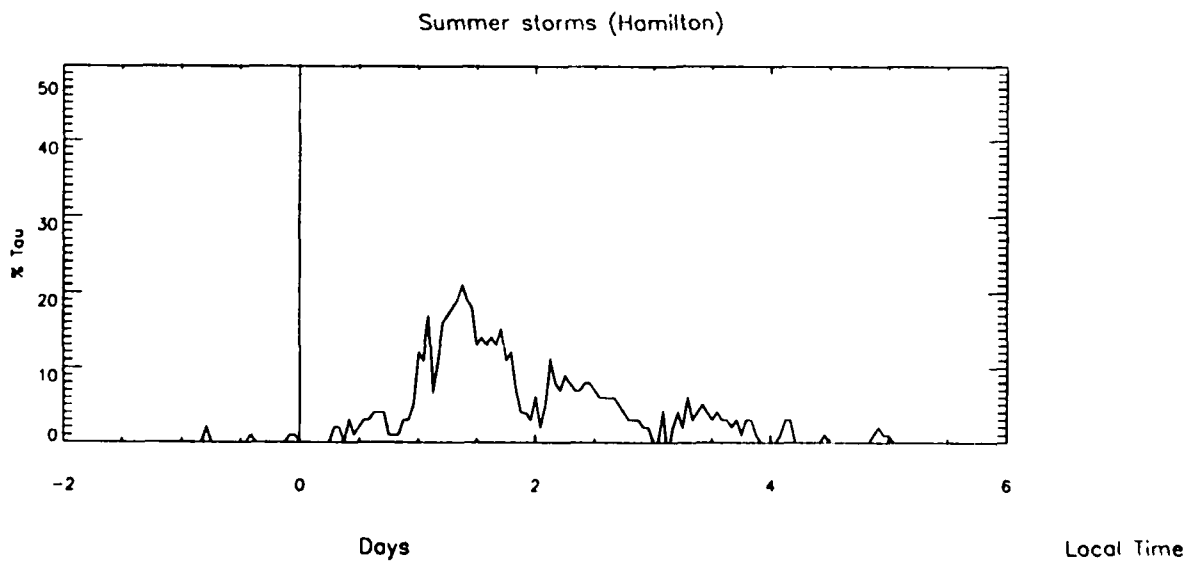
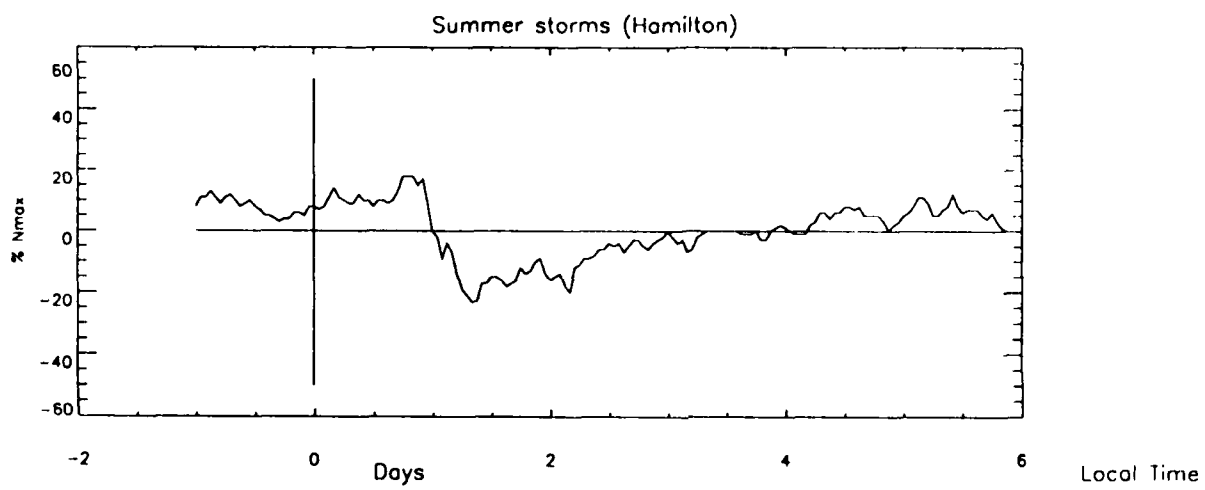
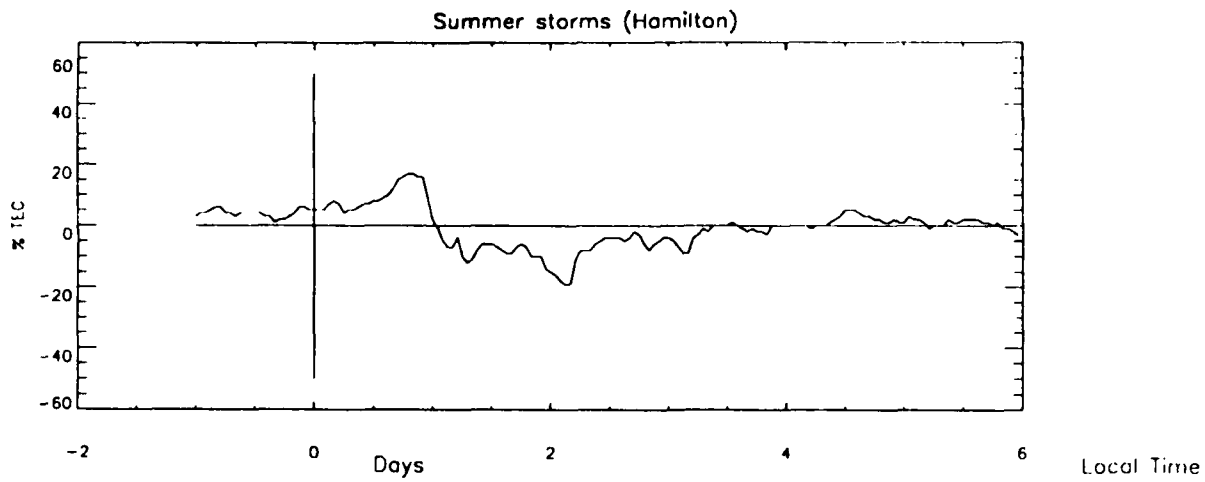


Figure 12. Average storm patterns for storms in summer months.

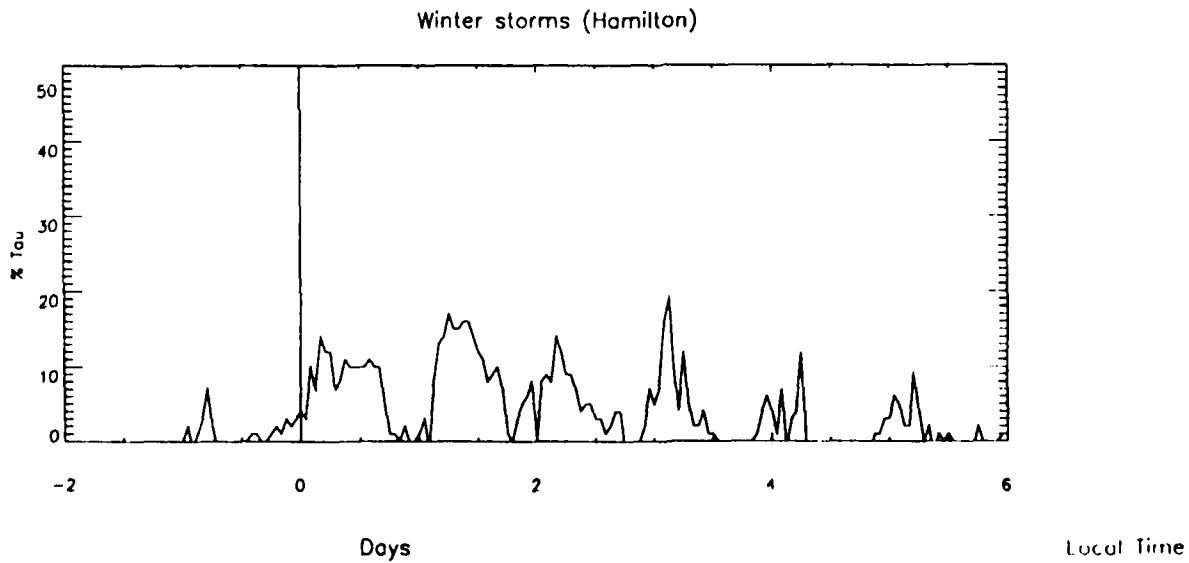
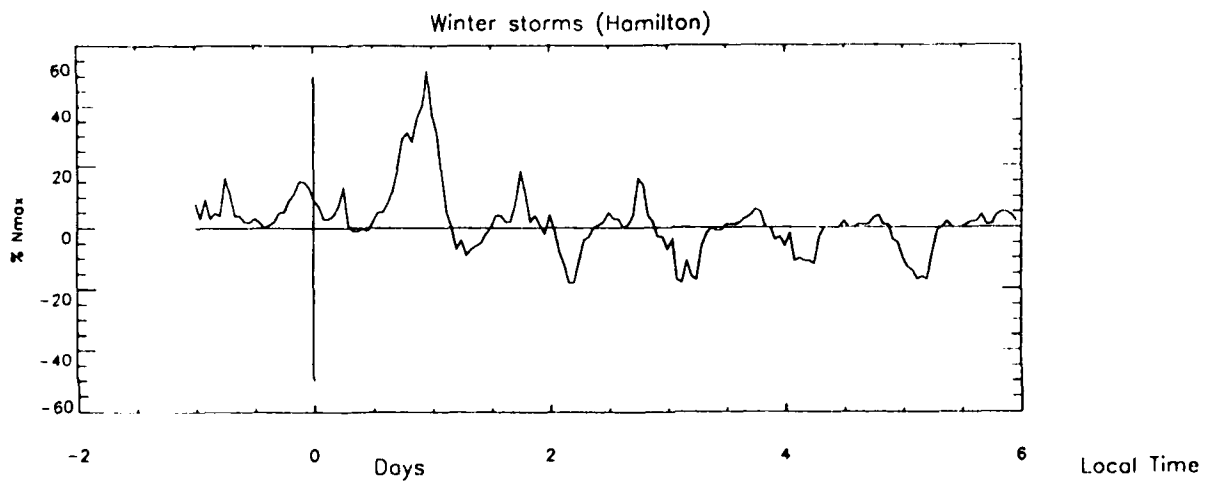
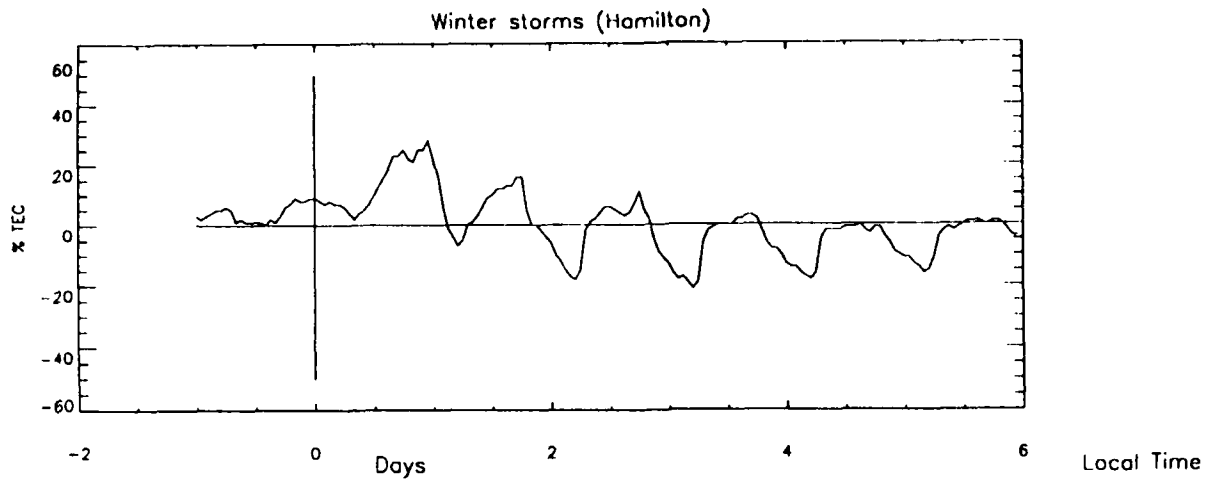


Figure 13. Average storm patterns for storms in winter months.

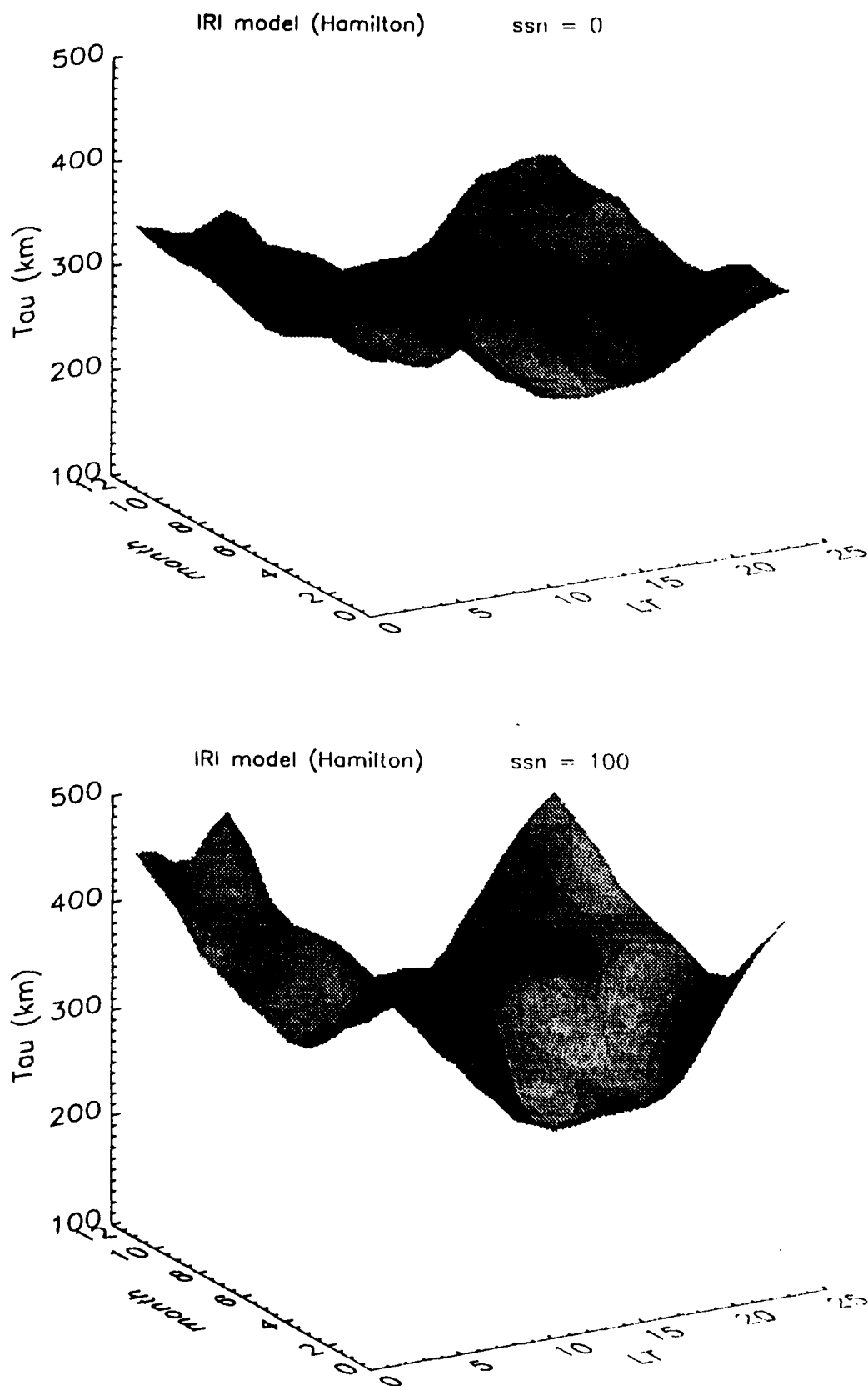


Figure 14. The predicted variations of slab thickness in the IRI model over Hamilton.

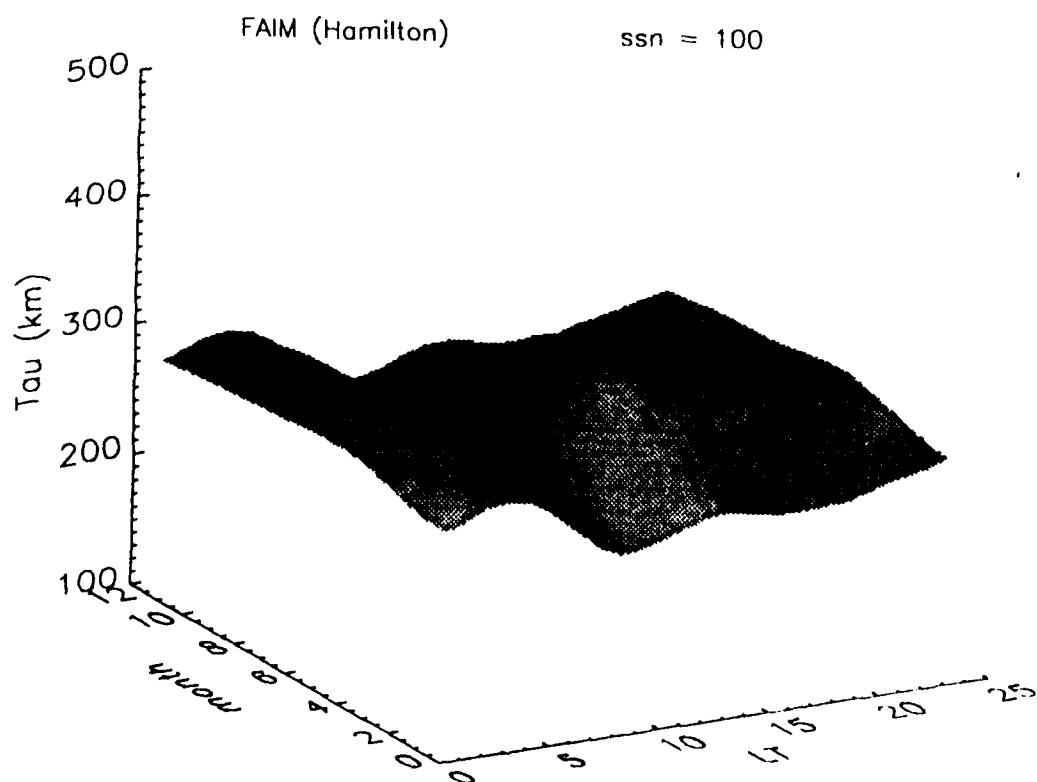
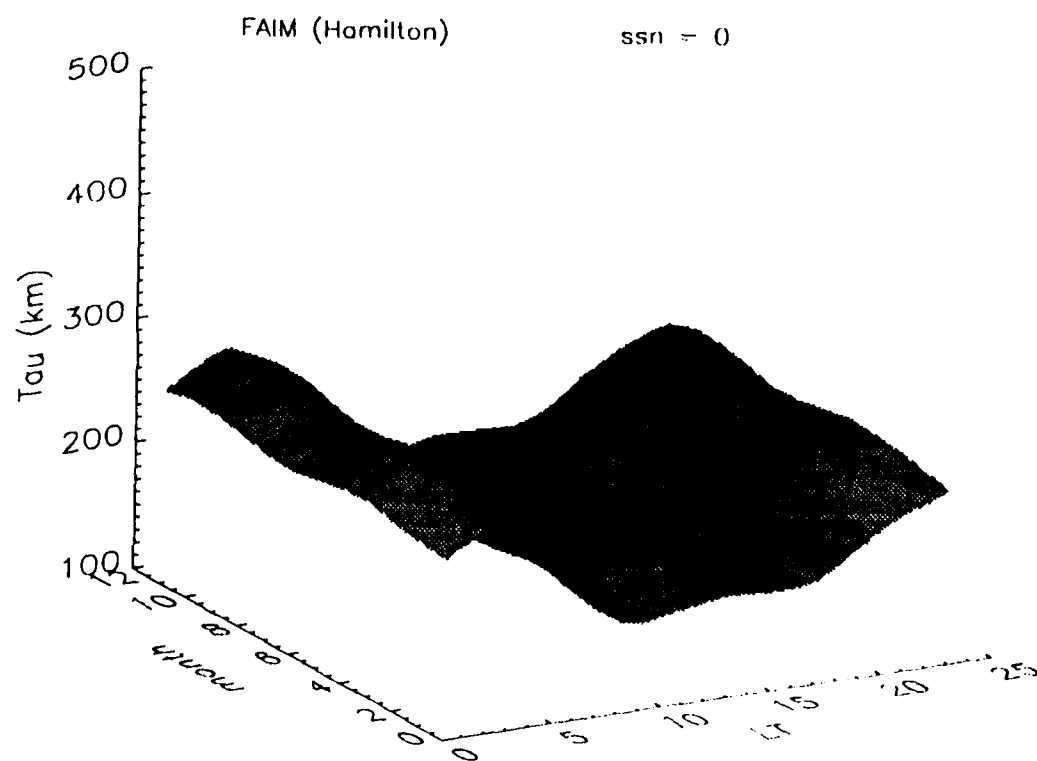


Figure 15. The predicted variations of slab thickness in the FAIM model over Hamilton.

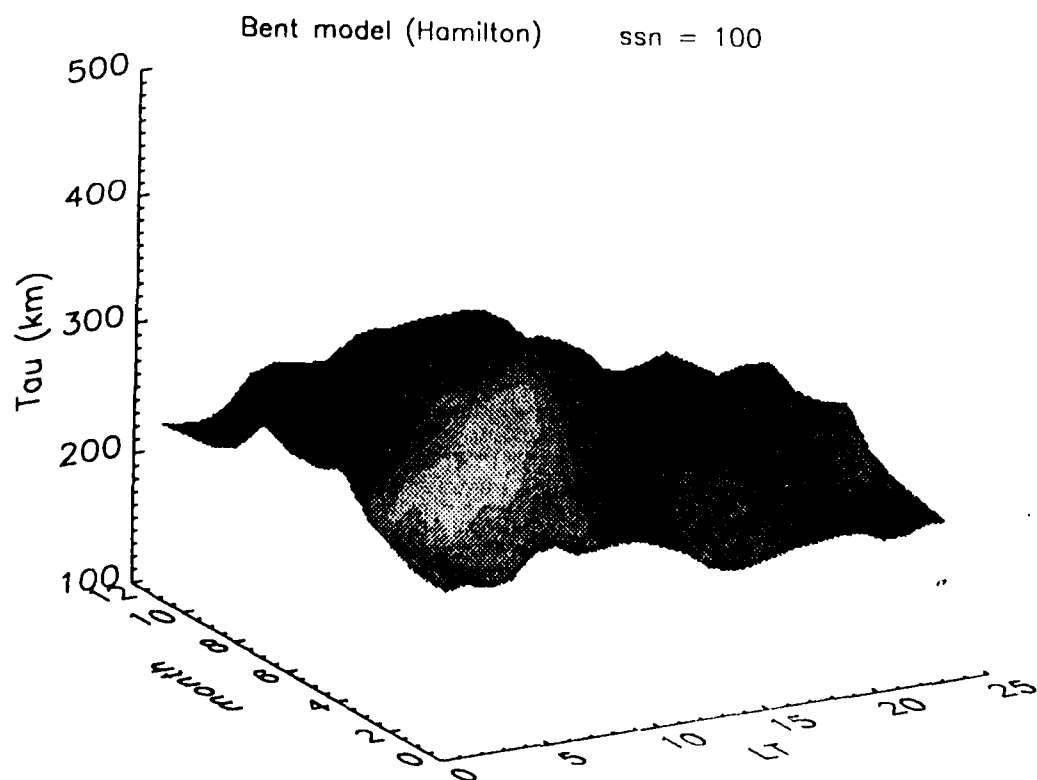
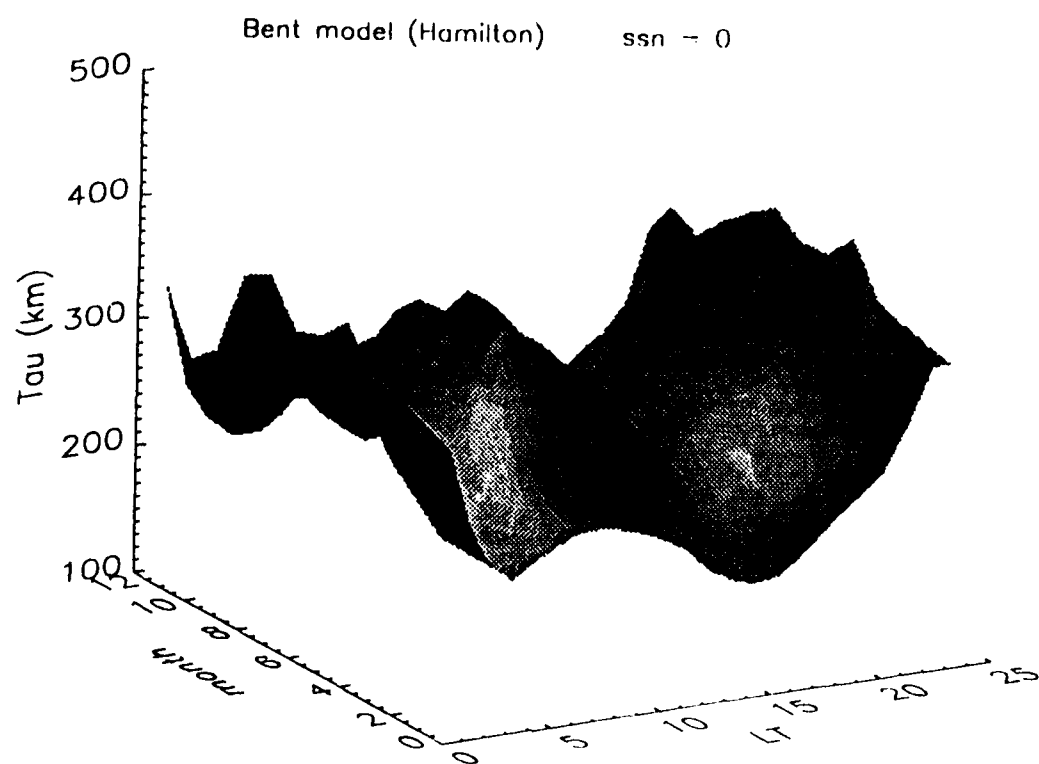


Figure 16. The predicted variations of slab thickness in the Bent model over Hamilton.

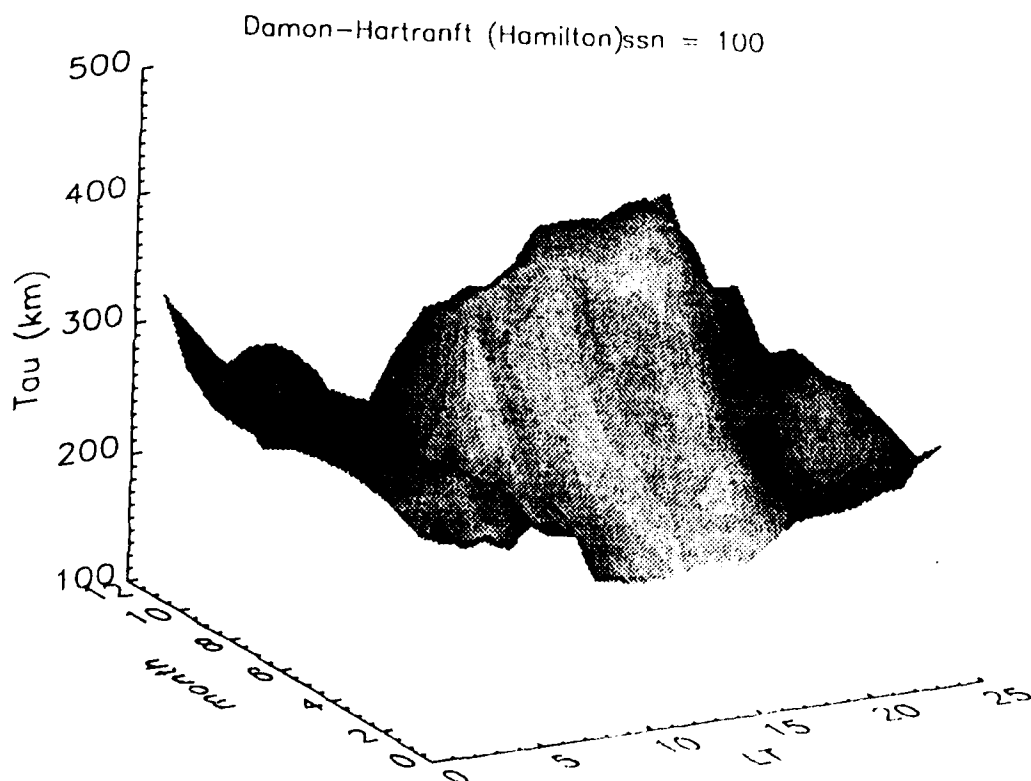
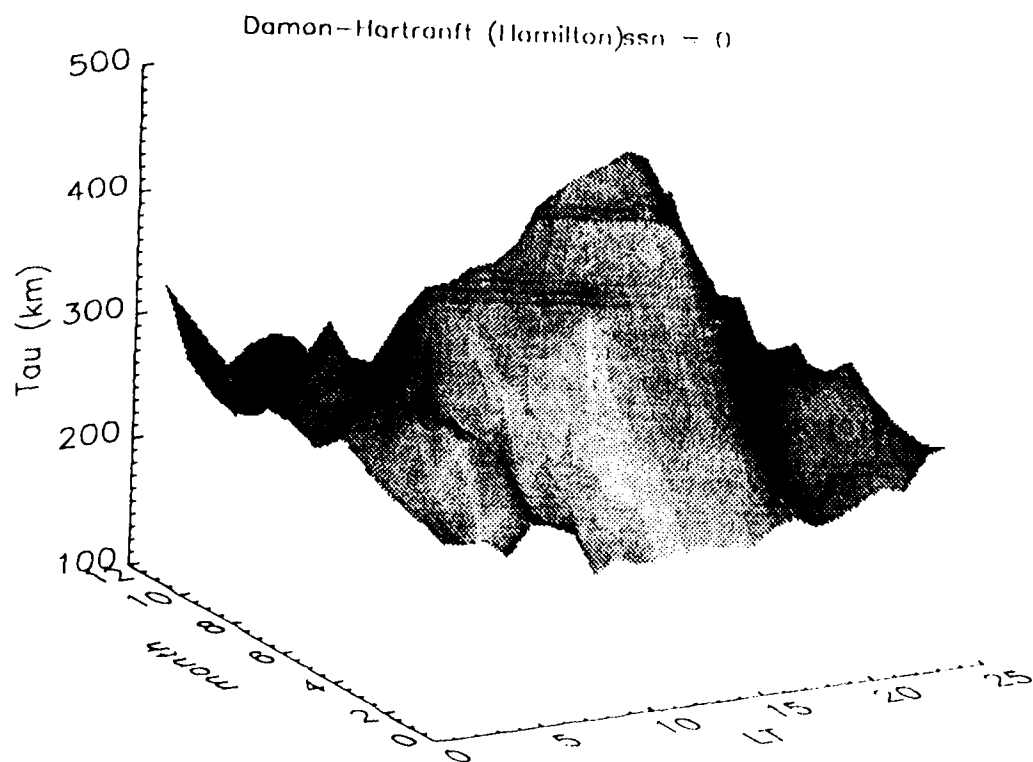


Figure 17. The predicted variations of slab thickness in the Damon-Hartranft profile model over Hamilton.

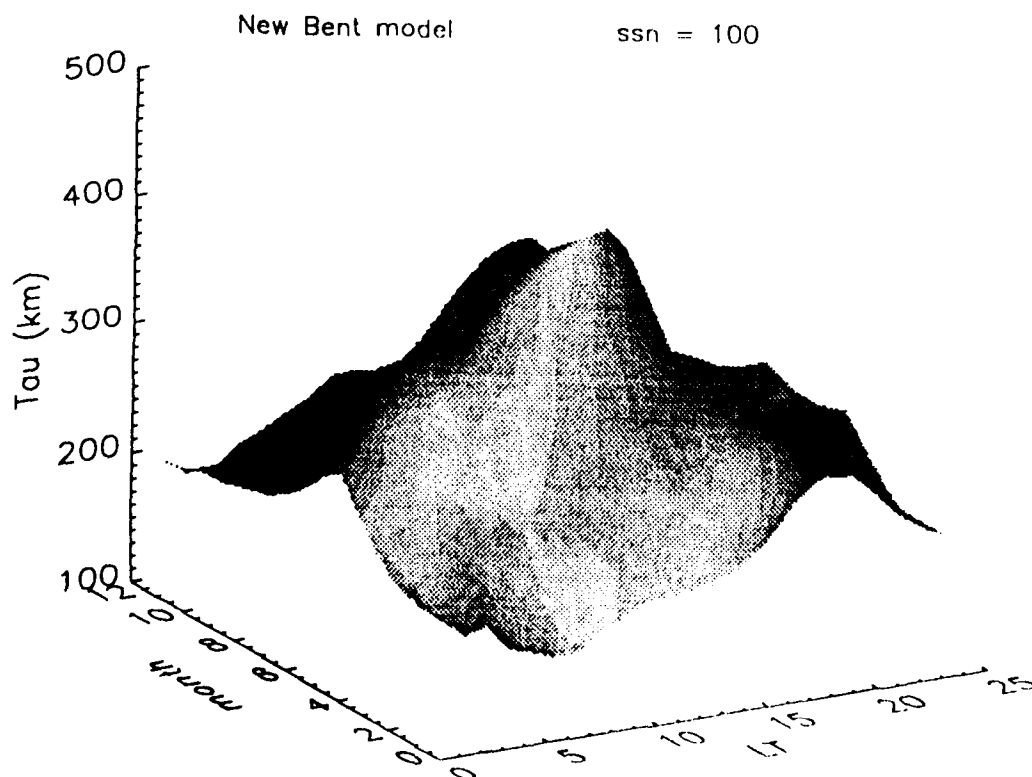
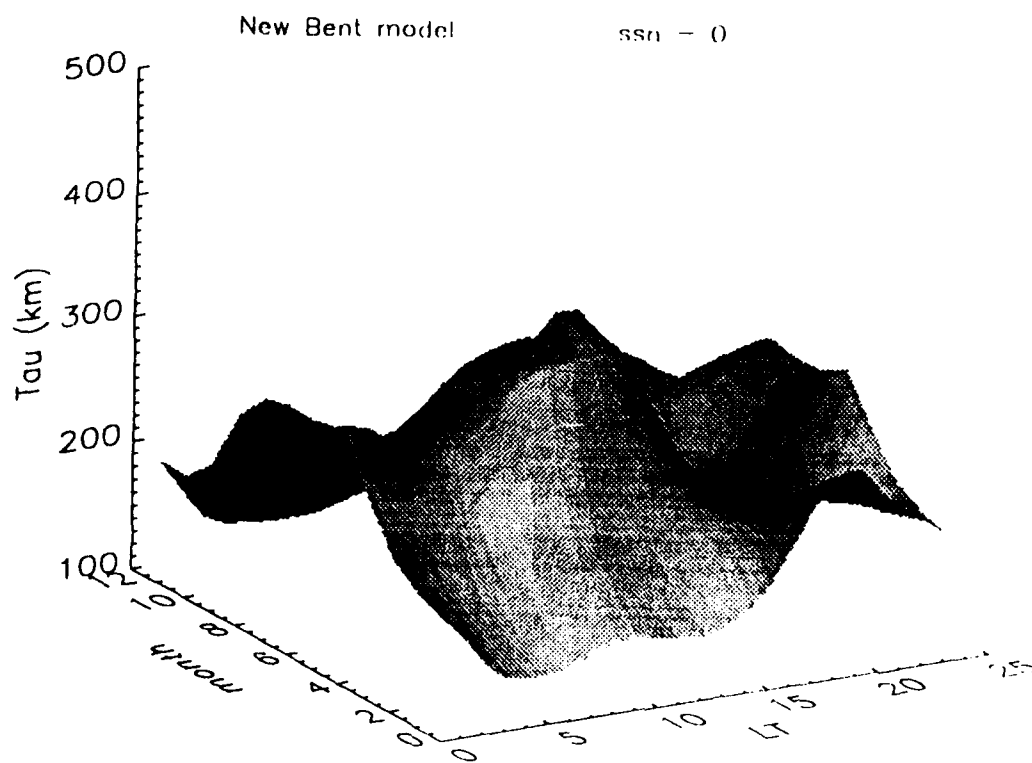


Figure 18. The predicted variations of slab thickness in the adjusted Bent model over Hamilton.

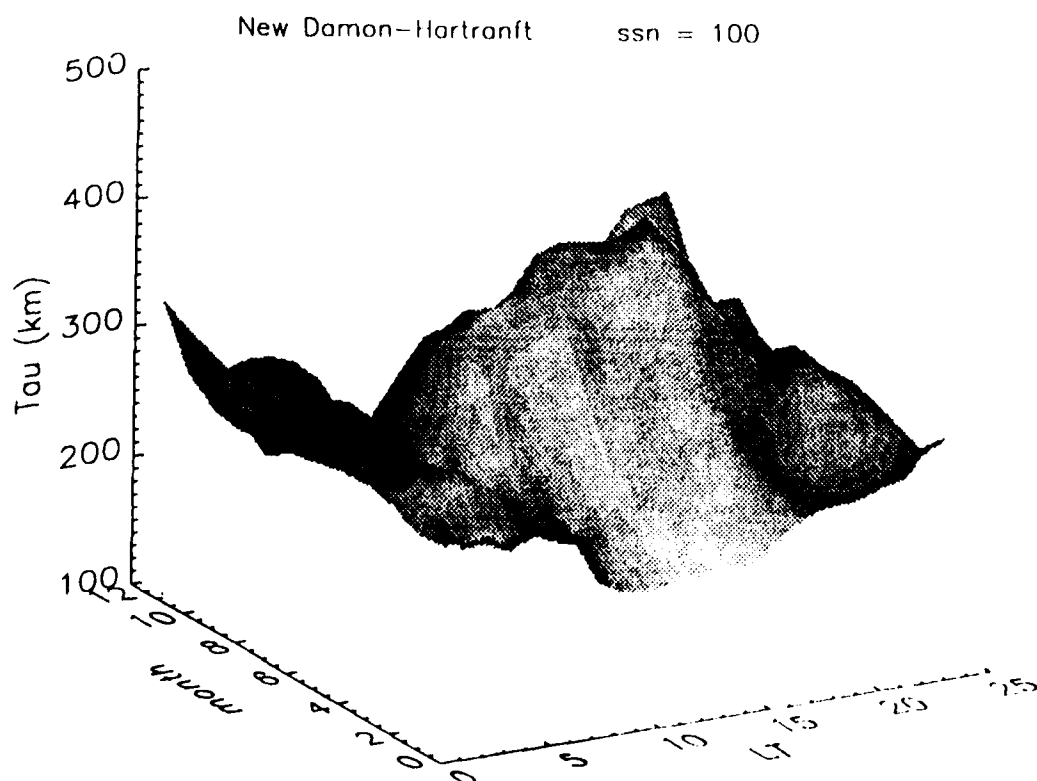
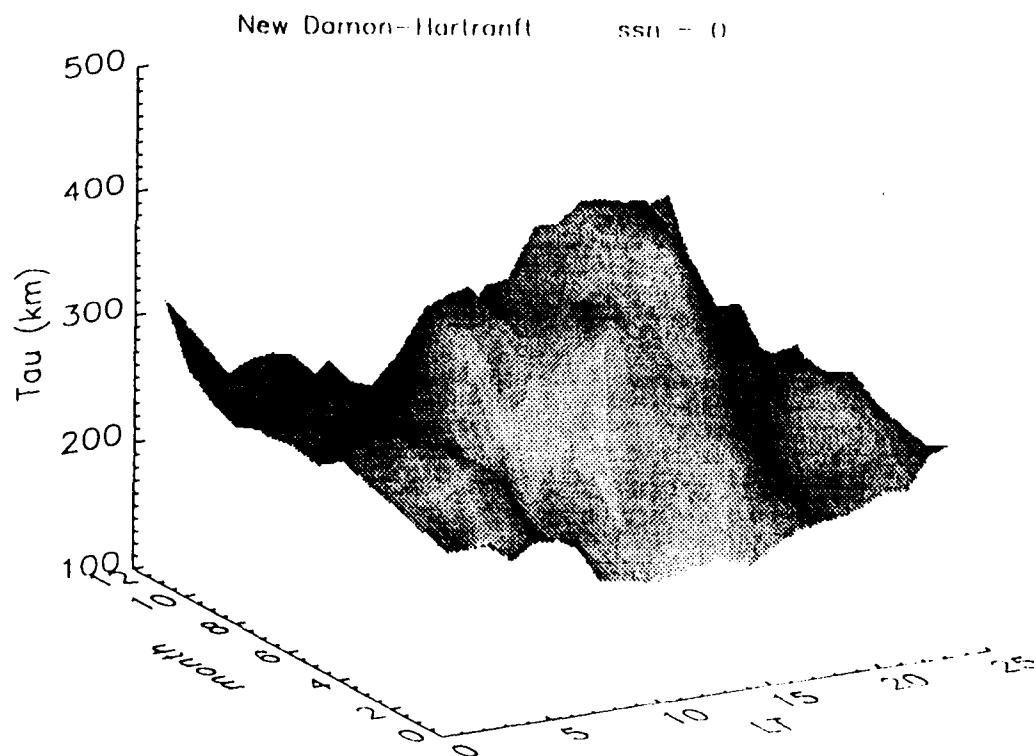


Figure 19. The predicted variations of slab thickness in the adjusted Damon-Hartrnft profile model over Hamilton.

TABLE 1.

Coefficients of the numerical model
of slab thickness over Hamilton, MA

1	967.669128	-55.940933	-3.312304
1	1.333233	-0.126093	-0.038230
2	10.745616	44.706707	-4.471966
2	-0.233183	0.016534	0.047228
3	6.933283	9.519387	2.733578
3	-0.013183	-0.016604	-0.027225
4	-14.580335	-5.529068	-0.066501
4	0.091433	-0.028822	0.007448
5	-0.982883	-2.885091	-0.473851
5	0.019917	0.003953	-0.006318
6	-10.944301	-26.289600	1.448303
6	-0.260650	0.179118	0.010151
7	7.294633	-26.680597	-4.396414
7	0.003350	0.288927	0.026614
8	-5.232584	-4.721190	-1.157496
8	0.020050	0.011456	-0.001325
9	-11.624967	1.571378	-1.127858
9	0.047650	-0.033589	0.007383

APPENDIX.

An example of a Fortran routine that evaluates the monthly mean slab thickness using the listed coefficients. Takes month, Local Time and monthly sunspot number as input.

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

```

      program maketau
c
c   Use the file of coefficients to predict slab thickness
c   for a specified month, hour and sunspot number.
c
      integer orderd, ordera
c
      real aazero(9), aan(4,9), abn(4,9)
      real bazero(9), ban(4,9), bbn(4,9)
c
      real a(9), b(9)
      real coeffs(9)
      real azero, an(4), bn(4)
c
      integer month, hour
      real ssn
c
      real sines(9,24), coses(9,24)
      real asines(9,12), acos(9,12)
c
c   Input the month, ssn, and hour (LT)
c
      write(6,*) ' Enter the desired month, ssn and Local Time'
      read(5,*) month, ssn, hour
c
c   set up the convenient array of cos and sin values for the Fourier fits
c
      pi = acos(-1.0)
      scale = pi/12.0
      ascale = pi/6.0
c
      do 101 i = 1, 9
c diurnal (hours LT : 00-23)
      do 102 j = 1, 24
         angle = float(i * (j-1)) * scale
         coses(i,j) = cos(angle)
102      sines(i,j) = sin(angle)
c and annual (months 1-12)
      do 103 j = 1, 12
         angle = float(i * j) * ascale
         acos(i,j) = cos(angle)
103      asines(i,j) = sin(angle)
101      continue
c
c   Read in the coefficients
c
      open(unit=1,name='coeffs.dat',status='old',form='formatted')
```

```

c  define the orders of the Fourier fits (Diurnal and Annual)
    orderd = 4
    ordera = 1

c  read in those annual coeffs
    do 200 k = 1, 2*orderd+1
        read(1,*) j, aazero(k), (aan(j,k),j=1,ordera), (abn(j,k),j=1,ordera)
        read(1,*) j, bazero(k), (ban(j,k),j=1,ordera), (bbn(j,k),j=1,ordera)
200    continue
    close(1)

c
c  First, use the annual Fourier stuff to generate the coefficients with
c  respect to ssn for the desired month
c
    do 1000 k = 1, 2*orderd+1
        tmpa = aazero(k)/2.0
        tmpb = bazero(k)/2.0
        do 1200 n = 1, ordera
            tmpa = tmpa + aan(n,k) * acosess(n,month) + abn(n,k) * asinss(n,month)
            tmpb = tmpb + ban(n,k) * acosess(n,month) + bbn(n,k) * asinss(n,month)
1200    continue
        a(k) = tmpa
        b(k) = tmpb
1100    continue
1000    continue

c
c  Then, determine the diurnal Fourier coeffs for that ssn
c
    do 4000 k = 1, 2*orderd+1
4000    coeffs(k) = a(k) + b(k) * ssn

c  or, in the more usual Fourier parlance
    azero = coeffs(1)
    do 4010 k = 1, orderd
        an(k) = coeffs(k+1)
4010    bn(k) = coeffs(k+orderd+1)

c
c  Finally, regenerate the hourly value using those diurnal coeffs
c
    tau = azero/2.0
    do 2410 n = 1, orderd
2410    tau = tau + an(n) * cosess(n,hour+1) + bn(n) * sinss(n,hour+1)

    write(6,*) ' Thus Tau = ', tau

    stop
    end

```